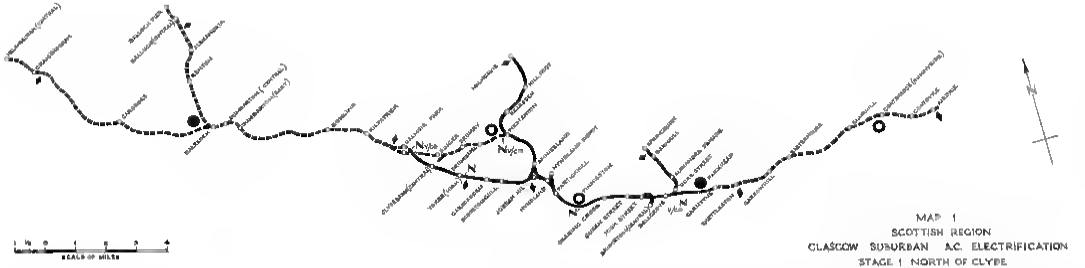
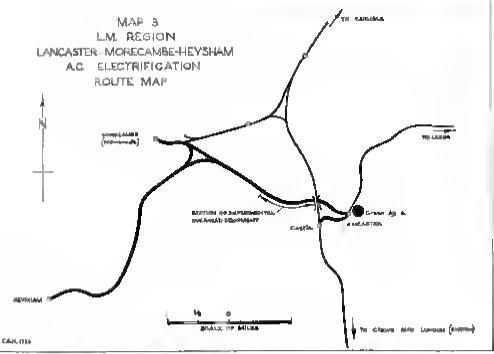
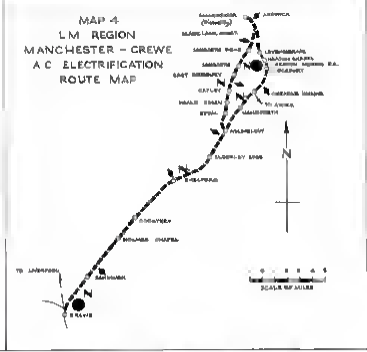
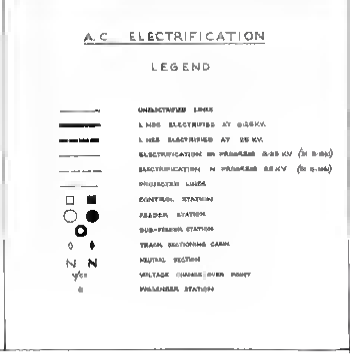


MAP 1
SCOTTISH REGION
CLASGOW SUBURBAN A.C. ELECTRIFICATION
STAGE 1 NORTH OF CLYDE
ROUTE MAP







MAP 2

EASTERN REGION A.C. ELECTRIFICATION

Note: Only Electrified Lines are Shown

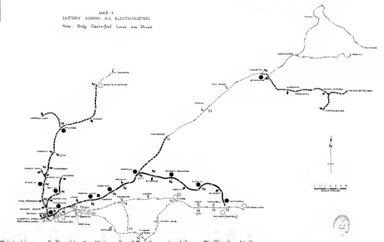


FIG 3

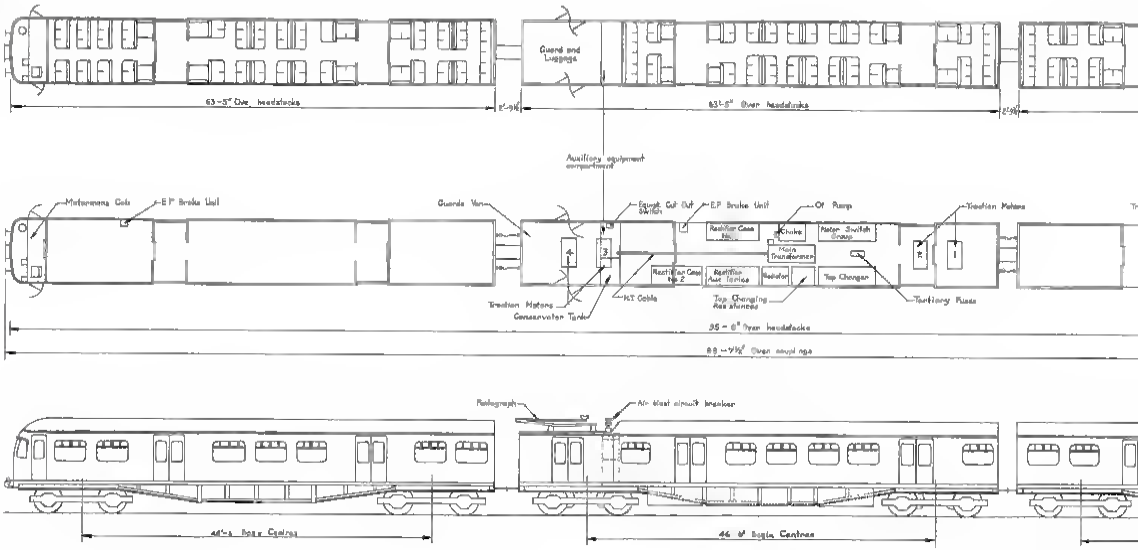


FIG 3

GLASGOW SUBURBAN ELECTRIFICATION - STAGE 1 - PHASE 1

LAYOUT OF MULTIPLE UNIT STOCK

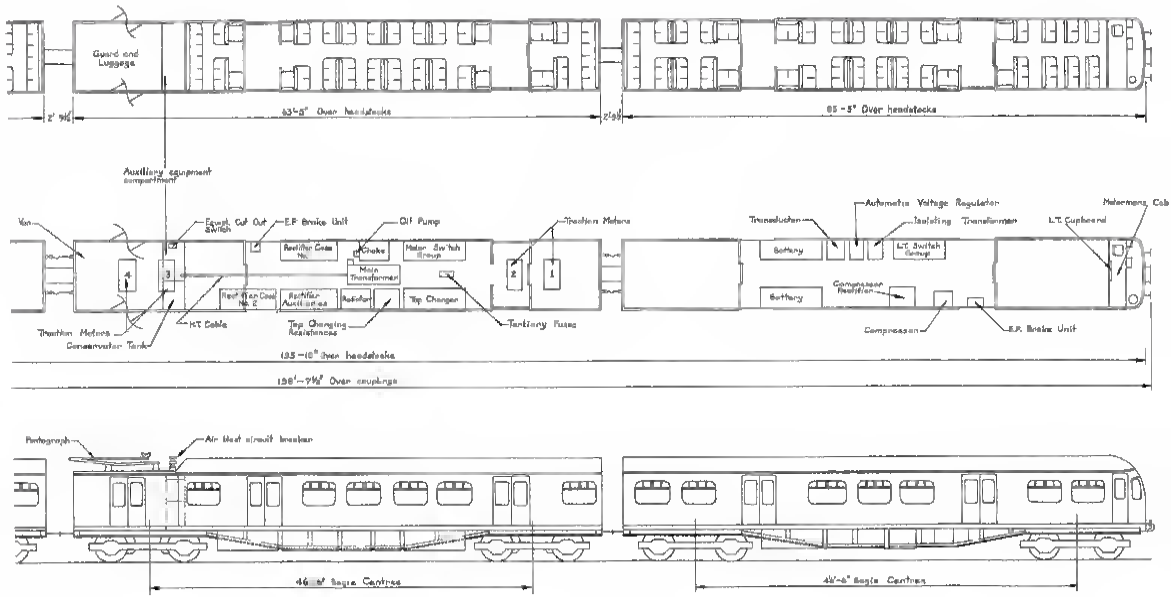


FIG 3

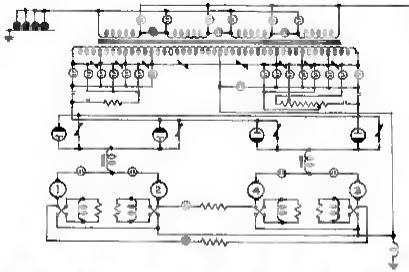
GLASGOW SUBURBAN ELECTRIFICATION - STAGE 1 - PHASE 1

LAYOUT OF MULTIPLE UNIT STOCK

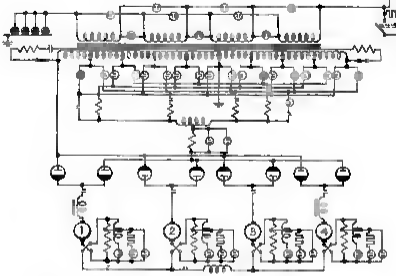
FIG. 4

FIG. 4 A.C. MULTIPLE UNITS, SIMPLIFIED POWE

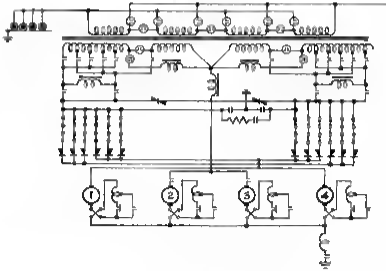
Sc. REGION, A.E.I. MANCHESTER



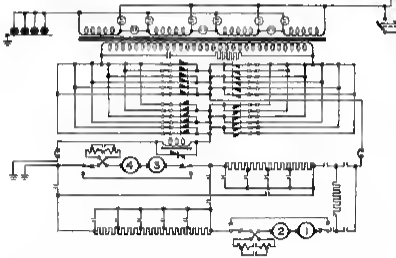
E. REGION, G.E.C.



E. REGION, ENGLISH ELECTRIC (S.A.S. STOCK)

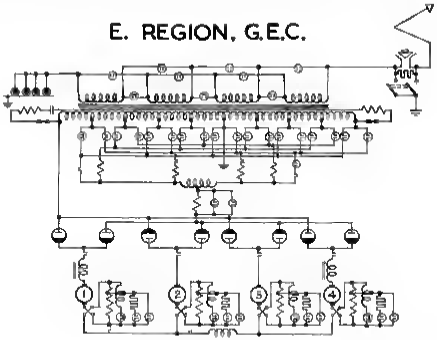


E. REGION, A.E.I. CONVERTED STOCK (1949)

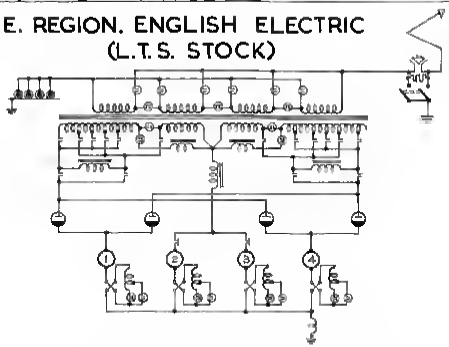


MULTIPLE UNITS. SIMPLIFIED POWER CIRCUITS as originally designed

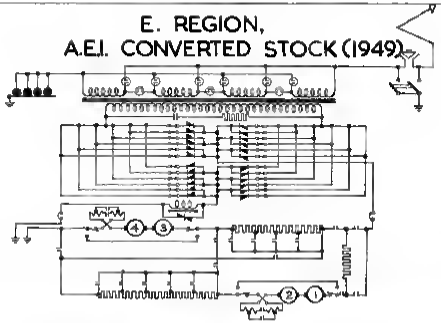
E. REGION, G.E.C.



E. REGION, ENGLISH ELECTRIC (L.T.S. STOCK)



E. REGION, A.E.I. CONVERTED STOCK (1949)



L.M. REGION, A.E.I. RUGBY

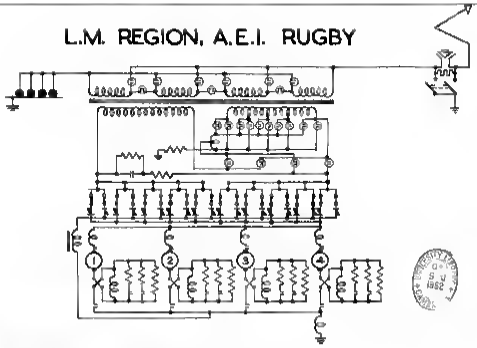
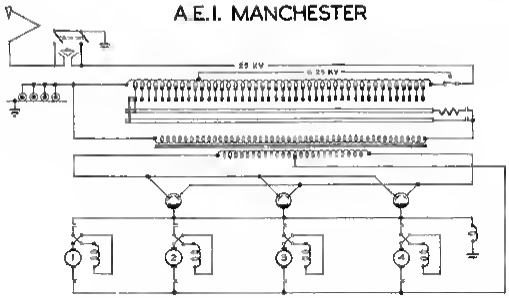
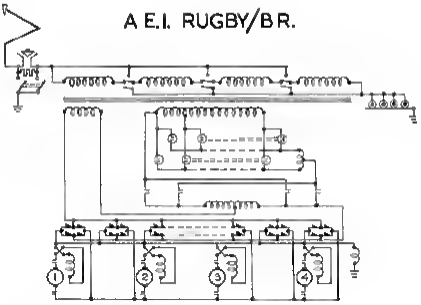


FIG. 5

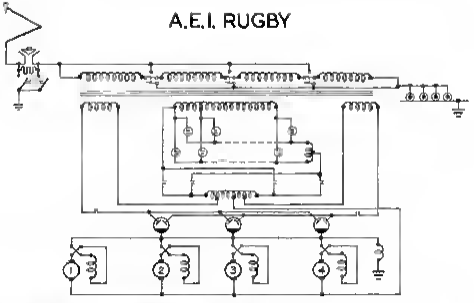
A.E.I. MANCHESTER



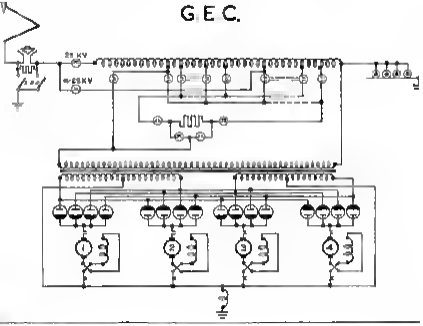
A.E.I. RUGBY/B.R.



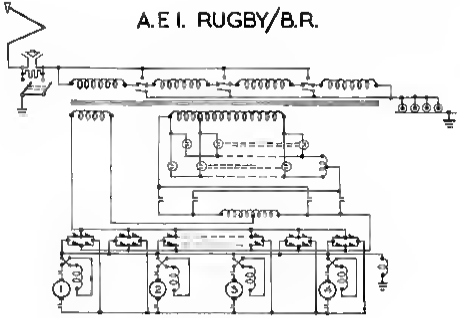
A.E.I. RUGBY



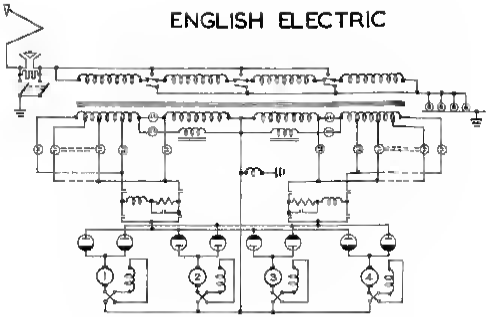
G.E.C.



A.E.I. RUGBY/B.R.



ENGLISH ELECTRIC



G.E.C.

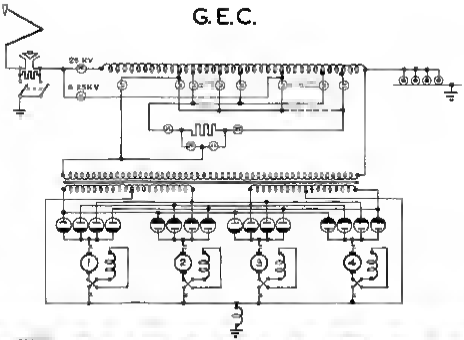


FIG. 5

A. C. LOCOMOTIVES

SIMPLIFIED POWER CIRCUITS

MINISTRY OF TRANSPORT,
ST. CHRISTOPHER HOUSE,
SOUTHWARK STREET,
LONDON, S.E.1.
17th March, 1962.

SIR,

I have the honour to report for the information of the Minister of Transport in accordance with the Order dated 20th December, 1960, the result of my Inquiry into the accidents that occurred on 13th and 17th December, 1960, in multiple-unit trains on the Glasgow Suburban electric service in the Scottish Region, and of my investigations into all other failures experienced in the operation of these services and of those on the other high voltage A.C. overhead electric systems in the Eastern and London Midland Regions of British Railways.

2. The accidents in the Scottish Region were two of a series of five transformer failures, the first of which occurred on 30th October, 1960, when a full day's trial was held prior to opening the public services on 5th November. The fifth occurred on 17th December, as a result of which the Scottish Regional General Manager, after consulting the British Transport Commission, decided to withdraw all electric train services forthwith in view of the possible danger which might arise from other similar failures.

3. I felt that I could not investigate the cause of these two accidents without taking into consideration the other transformer failures, and also the troubles that had been experienced with other electrical equipment on the Glasgow suburban trains which may have had a bearing on the transformer failures. As the investigation proceeded it became essential to check the design of the transformers in use in trains on other sections of British Railways electrified on the high voltage A.C. system to ensure that they were immune from certain weaknesses discovered in the Glasgow transformers. It further became necessary to take note of the failures on the other recently opened high voltage A.C. electrified sections of British Railways to ascertain whether they and the transformer failures in the Scottish Region were in any way inter-related and, in particular, whether the introduction for the first time on any railway of a dual high voltage A.C. system had any bearing on the problem.

4. I have been assisted in these investigations by Mr. F. J. Lane, O.B.E., M.Sc., M.I.E.E., a partner of Messrs. Preece, Cardew and Rider, and a member of the British Transport Commission's Panel of Consulting Engineers who was requested by the Commission to make an investigation into the transformer failures, and by Mr. E. L. E. Wheatcroft, M.A., M.I.Mech.E, M.I.E.E., a partner of Messrs. Merz and McLellan, another member of the Commission's Panel of Consulting Engineers, who was requested by the Commission to make an examination of the failures of the traction motors and other associated equipment which have occurred on the North-East London suburban electric services in the Eastern Region. Mr. Lane, Mr. Wheatcroft and Mr. T. W. Wilcox, M.I.E.E., another partner of Messrs. Merz and McLellan, have collaborated to ensure that all aspects of the subjects under investigation have been covered.

5. In view of the public concern over the withdrawal of the electric trains from the Glasgow suburban service following the accident on 17th December, I prepared an interim report which was presented on 13th January, 1961. I also considered it equally desirable to prepare a second interim report on the failures in the North-East London multiple-unit trains, and my report was completed on 30th May, 1961.

6. This final report includes summaries of the information given in the interim reports, and I have added further information about all other relevant matters, both technical and administrative, in order to present a full and complete account of the difficulties experienced by British Railways since the opening, for the first time on any railway, of the dual high voltage system of A.C. electric traction as applied to multiple-unit trains running on intensive suburban services. My report is based on the evidence about the Glasgow transformer failures which was given in public on 22nd and 23rd December, 1960, on numerous meetings with all the interested parties, on my inspection of equipment both in service and at the manufacturers' works at home and abroad, on the extensive trials which have been carried out, and on the reports covering a great variety of subjects which I have received from the British Transport Commission and the Regional Managements, the Consulting Engineers and the Manufacturers.

The completion of this report has been postponed until all the difficulties experienced with the original equipments were resolved.

7. This investigation has shown that one of the principal causes of trouble was backfiring by mercury arc rectifiers (*a*) which over-stressed the transformers on the Glasgow and North-East London units. The faulty performance of the automatic power control equipment and the circuit-breaker, associated with the dual high voltage system have also contributed materially to the difficulties and failures of transformers, motors and auxiliary equipment.

(*a*) A backfire of a mercury arc rectifier is a short circuit between the anode and the cathode, and in the case of the main rectifier it produces a short circuit across the secondary winding of the main transformer.

(85271) B 2

The troubles experienced in the early days of operation have been overcome, as is demonstrated by the performance of the multiple-unit fleets during the last 18 months. Up to 31st December, 1961, they had run for nearly 20,000,000 miles and they are now adding to this impressive score by some 1,500,000 miles a month. I am satisfied that the units now in service will be as reliable, as effective and as safe as any other A.C. traction units in the world.

8. Those matters which are pertinent to this report are summarised in the parts which follow. They are:—

Part I. General Review.

Part II. The British Railways' high voltage A.C. system of electrification.

Part III. The accidents and failures on the Glasgow suburban A.C. electrified lines.

Part IV. The failures of the multiple-unit trains running on the North-East London (Eastern Region) A.C. electrified lines.

Part V. Experience with the other multiple-unit trains and with the A.C. electric locomotives.

Part VI. General Conclusions, Remarks and Recommendations.

PART I. GENERAL REVIEW

SECTION I. REVIEW OF THE EVENTS LEADING UP TO THE DECISION TO ADOPT THE DUAL HIGH VOLTAGE A.C. SYSTEM AND OF THE STEPS TAKEN TO IMPLEMENT IT

9. In order to appreciate the circumstances surrounding the serious failures of new electrical equipment on two important suburban systems, it is desirable to review the events leading up to the decision to adopt the dual high voltage A.C. system and of the steps taken to implement it.

The factors affecting the British Transport Commission's choice of this system as the future standard for British Railway electrification are given in the document " The System of Electrification for British Railways " which was puhlished hy the Commission in 1956.

Early Reports

10. In 1948, shortly after nationalisation, the Commission set up a joint Committee of the British Railways and London Transport to review the methods of railway electrification and to make recommendations as to the systems to be adopted in future. In 1951 the Commission accepted the Committee's recommendation that the 1,500 volts D.C. overhead system should he adopted as standard, except for the Southern Region third rail and the London Transport fourth rail systems.

The Committee did not, however, rule out the possibility of using 3,000 volts D.C. or high voltage A.C. on secondary lines with light traffic. The Commission accepted this view, and authorised the restoration of the high voltage A.C. electric services on the Lancaster–Morecambe–Heysham line but at single phase 50 cycles in place of 25 cycles, as well as the further extension of the 1,500 volts D.C. system in the Eastern Region.

The French Developments

11. During the next few years the A.C. experiment in Lancashire showed that this form of electric traction could be adapted for multiple-unit operation. But more important were the developments in France where, as a result of the success of the experimental line hetween Aix-les-Bains and La Roche-sur-Foron, the French Railways decided to adopt the 25 kV single phase 50 cycles A.C. system for the electrification of their railways in North-Eastern France.

The section hetween Valenciennes and Thionville hegan operation in July, 1954, and in May, 1955, the French Railways invited an international group of railway engineers to a Conference at Lille at which they presented the results of nine months' operation of the new system. These showed not only great economy in the cost of the fixed equipment hut that, contrary to earlier expectations, the A.C. locomotives were cheaper and lighter than their D.C. counterparts.

The results of this Conference fired the imagination of the railway engineers throughout the world, and high voltage A.C. electrification at industrial frequency was generally accepted as the system for the future in those countries not already deeply committed to one of the other forms of electric traction.

The British Railways Modernisation Plan

12. Prior to this Conference, plans had heen made for the modernisation and re-equipment of British Railways, and on 25th January, 1955, the Modernisation Plan was published. It included proposals for the electrification of all the suhurban lines reviewed in this report as well as the main line electrification from Euston to Birmingham, Crewe, Manchester and Liverpool, the completion of which has heen recently approved.

The Commission were now faced with the alternative of pinning their faith in the well established 1,500 volts D.C. system which they had accepted as standard in 1951 and which was in operation on the Manchester–Sheffield–Wath and the Liverpool Street–Shenfield lines or of embarking on the new high voltage A.C. system which held out the promise of greater economy and wider scope for technical progress in the future.

The Commission's decision

13. The Commission made a study of the comparative costs of electrifying the Euston–Crewe–Manchester–Liverpool lines at 1,500 volts D.C. and at 25 kV single phase 50 cycles A.C. This showed economic and technical advantages in favour of the A.C. system, and on 6th March, 1956, the Commission announced their intention to adopt this system as a standard for future electrification in

Britain, save in the Southern Region where the extension of the existing third rail system was the best course. This decision was subject to the approval of the Minister of Transport which was given on 7th June, 1956.

It was indeed a bold and courageous step to take because it involved the abandonment of a policy first adopted as standard in 1932 and later confirmed in 1951 by the joint Committee; it required the rapid development of a new system of electric traction with which British manufacturers and Consulting Engineers had had little practical experience (but for the operation of three 3-car units on the Lancaster–Morecambe–Heysham line for little more than three years).

14. The decision was, however, supported by the British Electrical and Allied Manufacturers' Association, who agreed to co-operate with the Commission to the maximum extent and to accelerate development so as to have prototypes ready as quickly as possible and to produce the requisite number of completed units in time for the opening of the electrified services at the dates already announced. The task in front of the Commission and the British electrical industry was a formidable one if the programme set out in the Modernisation Plan was to be completed on time. It was made more difficult by two factors. In the first place the lines chosen for electrification included suburban routes carrying intensive passenger services. Secondly, the difficulty and expense of obtaining sufficient electrical clearances between live conductors and the overhead structures led to the adoption of the dual voltage system with automatic changeover, namely, 25 kV as the general standard and 6·25 kV in the restricted areas.

Orders for equipment

15. In March, 1956, provisional orders were given for the electrification of two "pilot" schemes at 25 kV single phase 50 cycles A.C., namely, the Colchester–Clacton–Walton lines in the Eastern Region and the Styal line, a convenient loop which formed part of the Crewe–Manchester electrification. These routes were equipped as rapidly as possible to enable tests to be made of the fixed equipment and to provide lines over which trial running of prototypes could be undertaken well in advance of the opening for public services of the suburban electrifications. The extent to which these facilities were used is described in Section VI.

16. There was little time to lose if the Modernisation programme was not to be delayed and the Commission invited tenders for locomotives and rolling stock from British firms of high reputation, even though their experience of A.C. traction was limited or confined to D.C. traction. Their object was to cast their net as widely as possible among the established firms so as to spread the load of production. Their decision also gave the electrical industry in general the opportunity of entering a new and expanding field of electric traction. The industry welcomed the decision and accepted the responsibility of producing service equipment in considerable quantity before prototypes had been fully tested.

Specifications

17. Specifications were drawn widely. The operating conditions and the performance and duties expected from the stock were set out in detail, as well as essential requirements such as loading gauges, clearances, axle loads and the like, for which rigid standards were obligatory. Design restrictions were kept to a minimum to allow full scope to the Contractors to develop their technical knowledge and initiative to the best effect. D.C. traction motors rather than A.C. were stipulated and a few items of equipment, of which there was not at that time a satisfactory British source of supply, were purchased from abroad or else manufactured under licence.

The Commission's Chief Electrical Engineer did not attempt to undertake the highly specialised task of designing complicated electrical equipment and circuits which he considered could only be done by the manufacturers, and for which he had not the staff. The specifications were based on relevant B.S.I. specifications wherever possible, but great faith was placed in those manufacturers who were known to be experts in the field of electric traction.

Orders for equipment

18. The orders for the electrical equipment for the multiple-unit suburban trains were placed at the end of 1956 and for the locomotives in 1957. The allocation is set out in Tables 3 and 10.

The Consulting Engineers' Panel

19. Following the publication of the Modernisation Plan in January, 1955, the Commission's Technical officers met representatives of the Association of Consulting Engineers to discuss the manner in which they could best assist the Commission in the furtherance of their Plan. No decision was

taken regarding their employment in connection with electrification, but in August, 1956, the Commission agreed to set up a small panel of Consulting Engineers to advise them on such matters affecting electric traction which they might consider necessary.

Since then members of the panel have reported on a number of problems including lighting arresters for locomotives and multiple-units and the design of the overhead changeover arrangements between 25 kV and 6·25 kV, and the provision of secondary insulation on overbridges and tunnels to reduce clearances. They have also made economic and technical reports on the merits of electric traction on various routes, but they were not called in to advise on the specifications of the new electrical equipment or to help in its examination and testing.

20. As already explained, Mr. F. J. Lane of Messrs. Preece, Cardew and Rider, and Mr. E. L. E. Wheatcroft and Mr. T. W. Wilcox of Messrs. Merz and McLellan, have been actively engaged in the investigations into the troubles that have occurred since the electrified systems were brought into use.

PART II. THE BRITISH RAILWAYS' HIGH VOLTAGE A.C. SYSTEM OF ELECTRIFICATION

Section II. The Overhead Equipment

The extent of the system

21. The extent of the routes covered by this report is given in Table 1 and illustrated by Maps 1 to 4. They include the Lancaster–Morecambe–Heysham line on which the first trials were conducted.

Table 1. The extent of the electrified system

	Route miles			Single track miles
	25 kV	6·25 kV	Total	Total
Scottish Region				
Glasgow suburban Stage 1 Phase 1	32	20	52	113
Eastern Region				
Colchester–Clacton–Walton	24	—	24	48
North-East London suburban	24	25	49	113
Liverpool Street–Shenfield–Southend (Victoria) ..	—	42(*a*)	42	154
Shenfield–Chelmsford	10(*a*)	—	10	20
London Midland Region				
Crewe–Manchester	44	—	44	217
Lancaster–Morecambe–Heysham	—	10(*b*)	10	19
Total miles ..	134	97	231	684

(*a*) Converted from 1500 volts D.C.
(*b*) Energised at 6·6 kV.

22. The lines are electrified on the high voltage single phase 50 cycles A.C. system. The normal line voltage is 25 kV, but on account of the restricted clearances of many tunnels and bridges, some long sections are energised at 6·25 kV; this has enabled the permissible clearance from load gauge to structure to be reduced from 23 in. for 25 kV to 11 in. for 6·25 kV. The rolling stock operating on the sections equipped for dual voltage have automatic voltage selection and changeover.

General description

23. The overhead equipment comprises a single cadmium copper contact wire supported from a catenary in diverse ways, depending upon the speed of the trains and the location. The equipment is the same for 25 kV and 6·25 kV except that smaller insulators are used for the lower voltage; on the Liverpool Street–Shenfield–Southend–Chelmsford converted lines most of the original 1,500 volts D.C. equipment has been retained.

The normal height of the contact wire is 16 ft. above rail level but under low tunnels and bridges where the loading gauge is 13 ft. 1 in. it is reduced to 14 ft. on the 25 kV lines and 13 ft. 5 in. on the 6·25 kV lines; at public level crossings it is increased to 18 ft. 6 in. for 25 kV and 18 ft. for 6·25 kV.

Neutral sections

24. A feature of the system is the provision of neutral sections with automatic operation of the traction unit's main circuit-breaker when the train passes through them. These sections are installed at Feeder Stations and mid-point Track Sectioning Cabins to avoid paralleling two different phases of the power supply. They are also used where there is a change of line voltage.

The neutral sections comprise three parts, so arranged that one is always " dead " during the passage of the pantograph.

There are two types:—

(i) Carrier wire type. This is the standard type. It consists of four overlap spans in series normally covering a distance of about 270 ft. over which current cannot be collected.

(ii) Section insulator type. This is used where space is limited and speeds are 60 m.p.h. or less; it is merely four section insulators in series at 40 ft. intervals. In this case the dead section is only 120 ft. long.

The neutral sections are provided with ground magnets suitably placed in advance and in rear of them. The first magnet causes the train circuit-breaker to open before a train enters the neutral

section, and the second magnet enables the circuit-breaker to reclose automatically after the train leaves the neutral section. These magnets also initiate the operation of the automatic power control equipment on the train, as described in para. 65.

Power supply

25. The method of power supply is fundamentally similar on all the electrified lines. It provides a duplicate supply to all tracks by individual feeds to either end of each of the sections into which each track is divided. The protection system ensures that under all normal fault conditions the power supply is automatically cut off the faulty section of track and maintained on all the other sections.

Power at 25 kV single phase is taken through step-down transformers from the national grid to the railway Feeder Stations whence it is fed direct to the 25 kV overhead system. Power for the 6·25 kV system is obtained from the railway 25 kV supply by means of step-down transformers installed in railway Sub-Feeder Stations or direct from the supply authority through their step-down transformers.

Feeder Stations and Track Sectioning Cabins

26. The 25 kV supply is taken in duplicate cables through circuit-breakers to the busbars in the railway Feeder Stations, and thence the power is fed through track feeder oil circuit-breakers to the various sections of the overhead line. The overhead line is divided electrically by Track Sectioning Cabins provided with circuit-breakers and isolating switches. The track feeder circuit-breakers are equipped with automatic re-closing relays, but so far this feature has not been brought into service.

Protection

27. The circuit-breakers open automatically under fault conditions in the circuit they protect. Incoming circuit-breakers operate on power supply transformer faults and busbar faults and provide back-up protection to the track feeder circuit-breakers. Track feeder circuit-breakers open on overhead line faults and also if a fault develops in the electrical equipment of the traction unit between the pantograph and the high voltage terminal of the transformer primary winding.

The track feeder circuit-breakers are all equipped with "distance impedance" protective relays so designed that in normal circumstances the total time to clear a fault by cutting off power from both ends of the section varies from 0·26 seconds to 0·76 seconds depending upon its position, or infrequently up to 1·26 seconds.

Should the fault be of exceptionally high resistance, a thermal relay takes control and causes the breaker nearest to the fault to open within times varying from 12 seconds to several minutes, according to the magnitude of the fault current.

Should a circuit-breaker or its "distance impedance" relay fail to function, the back-up protection comes into play and the next breaker further back opens.

Booster transformers

28. The return path for the current collected from the overhead equipment is normally provided by both the earth and the running lines. The current system is thus unbalanced resulting in magnetic induction which affects neighbouring lines, such as telecommunication circuits. Booster transformers are installed sometimes with and sometimes without return conductors to reduce this unbalance to a negligible fraction. The booster transformers are large current transformers of unit ratio, with the primary windings in series with the contact wire and catenary and the secondary in series either with the running rails or with the special return conductor when provided. The effect is to enforce in the return path a current equal and opposite to the contact wire current, thus reducing the unbalance.

Remote control of power distribution

29. The circuit-breakers at Feeder Stations and Track Sectioning Cabins are operated remotely by supervisory control from railway Electrical Control Rooms. The control room accommodates a mimic diagram on which is represented the power supply system and the layout of the area under control. This diagram is so arranged that the Controller can see at a glance the position of each circuit-breaker and whether there are any discrepancies. Additional alarm lamps with audible alarms give warnings of any failure of supply, the opening of the circuit-breakers, and other discrepancies between the actual state of the system and that shown on the diagram.

The instructions lay down that the Controller shall close a track feeder breaker one minute after it trips automatically, but if it trips a second time he must assume that the fault is sustained and take appropriate action to find out the cause.

Section III. The Electrified Routes

Scottish Region. Glasgow Suburban A.C. Electrification

30. The first stage of the Glasgow suburban electrification covers the lines to the north of the River Clyde from Helensburgh in the west through Glasgow Queen Street (Low Level) to Airdrie in the east, as illustrated by Map 1. There are branches to Balloch, Milngavie, Bridgeton Central and Springburn. On the Helensburgh route both the direct line via Westerton and the Clydebank branch via Yoker are electrified. All are 2-track lines.

31. The first section to be completed was the Milngavie branch, energised at 6·25 kV. It was opened for trial running on 12th July, 1959. Other sections followed until the whole line was electrified by 14th September, 1960, and was ready for public services to begin on 5th November, 1960.

32. The outlying lines are energised at 25 kV, but on account of the restricted clearances of the tunnels and bridges the inner suburban area is energised at 6·25 kV, thus the voltage is changed twice on every journey between the two terminals.

Power is supplied from the 132 kV national grid through step-down transformers to the railway Feeder Stations at Parkhead, Dalreoch and Motherwell. The last named, which will supply power to the lines South of the River Clyde, supplies power at 25 kV to the Railway Sub-Feeder Station at Coatbridge. The 6·25 kV supply is obtained from the railway supply and is fed to the line through the Feeder Stations at Parkhead and Westerton, and the Track Sectioning Cabin at Dalmuir Park.

The Feeder and Sub-Feeder stations, except Motherwell, and the Track Sectioning Cabins, as well as the neutral sections, are shown on Map 1. The Control Room is at Cathcart which is south of the river and is not shown on the map.

Voltage changeover takes place at the neutral sections near Parkhead, Westerton and Dalmuir Park. The first two are of the carrier wire type, but Dalmuir Park is of the section insulator type. There are two other neutral sections where no voltage change takes place, one at Finnieston of section insulator type and other at Yoker of carrier wire type.

33. Conditions generally are severe with gradients up to 1 in 64, sharp curvature (minimum radius 14 chains) and tight clearances, especially in the tunnels. Stations are closely spaced (an average of 0·8 miles apart on the central area and 1¼ miles apart over the rest of the route) and the service is intense.

A total of 310 trains is run each week-day with peak traffic through Queen Street of 15 trains per hour in one direction and 14 trains per hour in the other.

Eastern Region. The Colchester–Clacton–Walton line

34. This was one of the pilot schemes and the first section was opened for trial running on 5th February, 1959, and the first public service over the whole route began on 13th April, 1959. It forms part of the Eastern Region electrification, and is shown on Map 2. The line was used for commissioning most of the new units required for the Eastern Region suburban electrification. The Colchester–Clacton line is 2-track throughout and the Walton branch is a single line.

35. The line is energised throughout at 25 kV with power supplied from the national grid to the railway feeder station near Colchester. Two neutral sections of the carrier wire type, half a mile apart, were provided on the Down line between Alresford and Thorington. The contact wire between them was energised at 6·25 kV for testing the voltage changeover equipment. Normally these neutral sections were kept closed and the voltage changeover was used only for testing the automatic power control of each new unit of the E.R. electrified stock. There is another neutral section of the section insulator type near Colchester but it is through connected at present because it will only come into use when the main line electrification from Chelmsford is completed.

There are three Track Sectioning Cabins, as shown on the map, and these are controlled from a temporary room alongside the Feeder Station at Colchester.

36. The line runs generally through open country with easy curvature and gradients, and operating conditions are not onerous. The distance between stations averages 2·2 miles and the service is light, averaging two Up and two Down trains per hour during peaks, and one per hour in each direction during off peak periods.

Eastern Region. The North-East London suburban lines

37. This comprehensive suburban electrification comprises the lines from Liverpool Street to Bishop's Stortford, via Bethnal Green and the Churchbury loop, with branches to Chingford, Enfield Town and Hertford East. It is illustrated by Map 2.

The main line and the branches are 2-track, apart from the 4-track section between Bethnal Green and Hackney Downs and the six tracks from Liverpool Street to Bethnal Green, which also carry the main line steam and diesel trains to and from Liverpool Street as well as the electric trains on the Liverpool Street–Shenfield–Southend (Victoria) and Chelmsford services.

38. The first section between Rye House and Hertford East, energised at 25 kV, was opened for trial running on 23rd May, 1960. The first 6·25 kV section between Cheshunt and Hackney Downs was brought into use for the same purpose on 30th September, 1960; public services on steam timings began on 14th November and on full electric timings on 21st November, 1960.

39. The overhead lines from Liverpool Street to Cheshunt on the main line and on the Chingford and Enfield Town branches are energised at 6·25 kV; those on the main line from Cheshunt to Bishop's Stortford and on the Hertford East branch are energised at 25 kV. Thus trains running on the busy Chingford and Enfield branches operate at 6·25 kV only, and trains on the main line and the Hertford East branch pass through one voltage changeover point on each journey.

Power is supplied to the four Feeder Stations, as shown on the map; Bishop's Stortford is at present only an emergency feeding point. The locations of the track Sectioning Cabins and neutral sections are also shown on the map. The system is controlled from the Romford Control Room which also controls the Liverpool Street–Shenfield–Southend (Victoria) electrified system.

40. Conditions on the Chingford and Enfield lines are severe with steep gradients (1 in 70 max.) and sharp curvature (7·6 chains minimum radius). The distances between stations average about a mile. The services to Bishop's Stortford and Hertford East are run at higher speeds with less frequent stops; the average distance between stations is 2 miles; curvature and gradients also are not so severe.

41. The train services were heavy when first introduced on 21st November, 1960, and peak traffic averaged 18 Up and 18 Down trains per hour in and out of Liverpool Street, with an off peak traffic of 14 Up and 14 Down per hour. Owing to the failure of many of the North-East London units the services were somewhat reduced on 12th December, but they have been sufficient to carry the heavy commuter traffic which has been developed by electrification. These results have been achieved largely by using stock destined for the London, Tilbury and Southend (L.T.S.) line.

Eastern Region. The Liverpool Street–Shenfield–Southend (Victoria) and Shenfield–Chelmsford electrification

42. In 1949 an electrified overhead system at 1,500 volts D.C. was introduced between Liverpool Street and Shenfield, and it was extended to Southend (Victoria) and Chelmsford in 1956. These lines are also shown on Map 2.

Following the adoption of the high voltage A.C. system as standard for British Railways, it was decided to convert this overhead D.C. system to A.C. in readiness for the opening of the new A.C. services in November, 1960. It was considered that the clearances already provided for 1,500 volts would be suitable for 6·25 kV A.C., and consequently the major part of the system (all except the Shenfield–Chelmsford line) was converted to this voltage. The Shenfield–Chelmsford line was converted to 25 kV on 20th March, 1961.

The power supply arrangements were kept substantially the same as for the D.C. system, but new switchgear was installed. The Feeder Stations, Track Sectioning Cabins and neutral sections are located as shown on the map.

43. The Liverpool Street–Shenfield lines carry a heavy suburban traffic with closely spaced stations: after a 4-mile run to Stratford the average distance between stations for the next 16 miles to Shenfield is only 1·3 miles. Curvature is not severe and gradients are not serious, except for the 3 miles long Brentwood Bank with a rising gradient on the Down line of 1 in 100 steepening to 1 in 85 near the summit.

The Shenfield–Southend line is undulating with ruling gradients of 1 in 100; there are some sharp curves, the minimum radius being 23 chains. Stations on this route are further apart; the average distance is 5 miles.

44. The Shenfield–Chelmsford line, energised at 25 kV, is the first stage of the extension of the electrification to Colchester. Operating conditions are not severe and curvature and gradients are not exceptional. There is a voltage changeover neutral section at the eastern end of Shenfield station.

45. A heavy service of electric trains operates on the Liverpool Street–Shenfield line and during the morning and evening peaks 25 trains enter and leave Liverpool Street in the hour; off peak services average 10 trains per hour in each direction. Between Shenfield and Southend the peak services average 9 Up and 9 Down trains in the hour, and off peak services average 3 trains per hour in each direction. At present the electric services on the Shenfield–Chelmsford line average 3 Up and 3 Down trains per hour during the peaks, and two each way per hour for the rest of the day.

Eastern Region. London, Tilbury and Southend line

46. During the course of my investigations the London, Tilbury and Southend (L.T.S.) line has been electrified on the dual voltage system and a limited passenger service of electric trains was started on 6th November, 1961. These lines have therefore been shown on Map 2 as a matter of interest.

London Midland Region. Crewe–Manchester electrified lines

47. The first stage of the London Midland Region electrification comprises the main line from Crewe through Wilmslow and Stockport to Manchester (Piccadilly), and the Styal line from Wilmslow through Styal to Longsight where it rejoins the main line just south of Manchester. The routes are illustrated by Map 4.

The Styal line was opened for trial running on 26th October, 1958, and was used as a pilot scheme for 25 kV electrification. The first section of the main line was opened for trial running on 1st October, 1959, and the whole line from Crewe to Manchester, including the Styal line, was opened for public passenger service on new electric timings on 12th September, 1960, though some trains had been hauled by electric locomotives from 12th June onwards. The full electric local passenger service between Manchester and Crewe was brought into use in June, 1961.

48. All the lines are energised at 25 kV with power supplied at Heaton Norris and Crewe. The Track Sectioning Cabins and neutral sections are sited as shown on the map. The system is controlled from the Crewe Control Room. The Crewe-Manchester line is a fast running main line with a substantial proportion of four tracks without severe gradients or curvature, and speeds up to 90 m.p.h. are permissible. The Styal line is a 2-track suburban route with stopping stations spaced at an average of 1·6 miles apart. The operating conditions are not severe.

49. This stage forms but a part of the London Midland electrification now under construction, which will extend from Euston to Birmingham, Manchester and Liverpool and embrace a number of subsidiary routes. Until the project is complete it is not economical to work electrically all the locomotive-hauled trains between Crewe and Manchester and consequently only some of them are electric-hauled at present. The daily electric train services at present average 20 loco-hauled and 98 multiple-unit trains in the Up direction and 28 loco-hauled and 99 multiple-unit trains in the Down direction.

London Midland Region. The Lancaster–Morecambe–Heysham line

50. This line was the first to be electrified on the new single phase 50 cycles A.C. system. Originally it had been electrified as early as 1908 by the former Midland Railway to test the use of 6·6 kV single phase *25 cycles* A.C. The original electric trains were withdrawn from service in 1951 on account of their age, but as the overhead equipment was in relatively good condition, it was decided in 1952 to use the line for carrying out experiments with stock operating at the commercial frequency of 50 cycles.

Trial running at the higher frequency began in November 1952, and the commercial service was opened on 17th August 1953.

51. The route, which is illustrated by Map 3, begins at Lancaster and runs to Morecambe and Heysham. Conditions are not difficult except for the rising gradient of 1 in 70 between the two Lancaster stations. The electric service numbers 34 trains each way daily between Lancaster and Morecambe, and most of these trains run on to Heysham.

Comparison of operating conditions

52. The operating conditions on the electrified lines vary considerably on account of the varying distances and speeds between stops, as can be seen from the accompanying Table 2.

Table 2. Multiple-unit trains. Operating conditions

Section of line	Number of cars per unit	Average distance between stopping stations	Average speed between stopping stations	Peak services	
		Miles	M.p.h.	Trains per hour Up	Down
Scottish Region					
Glasgow suburban services—					
Inner area	3	0·8	18	14	15
Outer area	3	1·25	22	14	15
Eastern Region					
Colchester–Clacton	4	2·2	26	2	2
North-East London lines—					
Liverpool Street–Chingford	3	1·0	27	9	9
Liverpool Street–Enfield	3	0·75	22	6	6
Liverpool Street–Bishop's Stortford	4	2·2	33	3(*a*)	3(*b*)
Liverpool Street–Hertford East	4	1·8	27	3(*a*)	3(*b*)
Converted lines—					
Liverpool Street–Shenfield	3	1·3	27	25(*c*)	25(*c*)
Shenfield–Southend	4	5·0	38	9	9
Shenfield–Chelmsford	4	4·2	40	3	3
London Midland Region					
Crewe–Manchester	4	2·9	38	2	2
Styal line	4	1·6	32	6	6

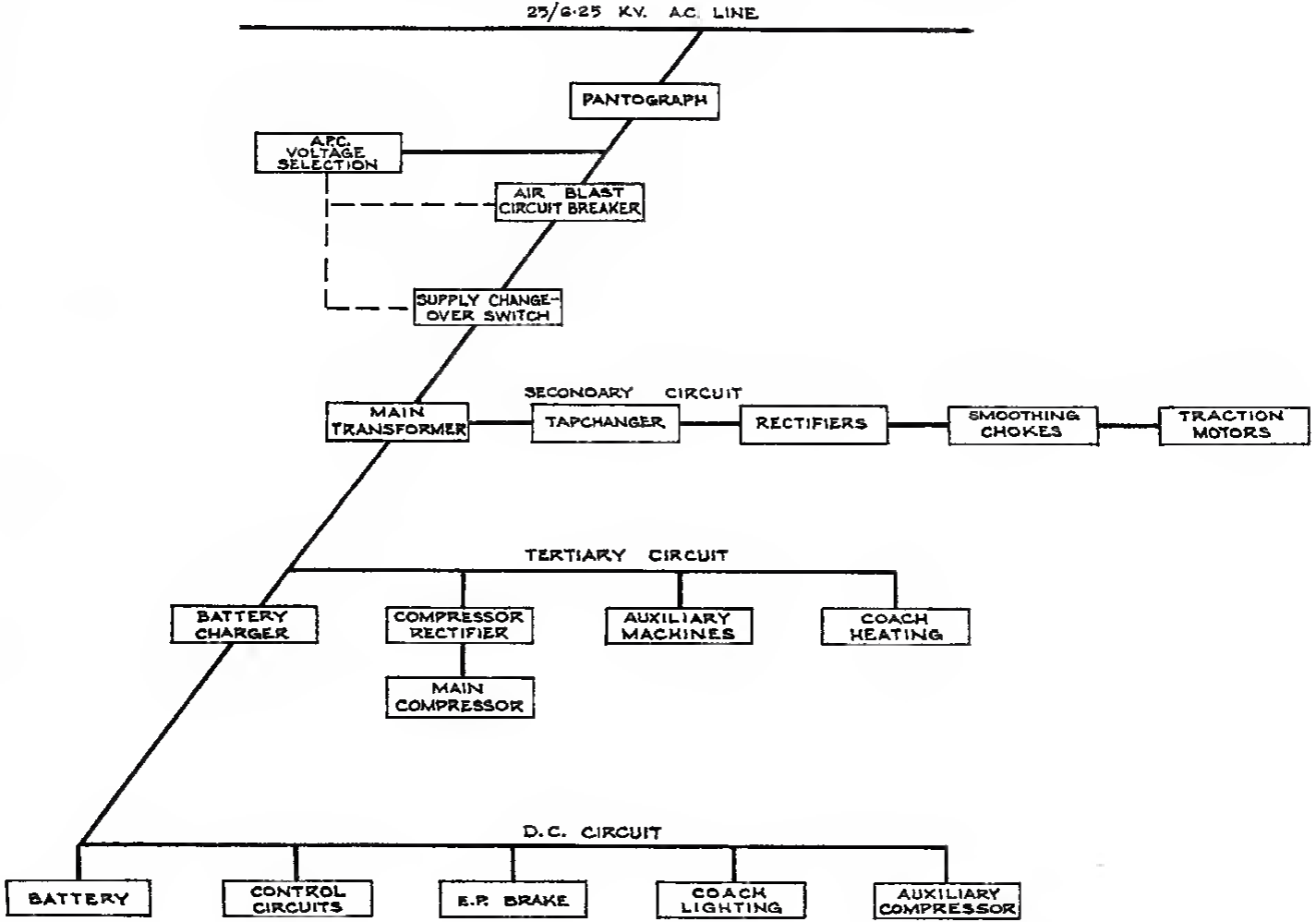
(*a*) Coupled together at Broxbourne.
(*b*) Divided at Broxbourne.
(*c*) Including the Southend and Chelmsford trains.

Table 3. The multiple-unit fleets

Region	Service	Number of units	Cars per unit	Cars built at	Major electrical contractor
Scottish	Glasgow suburban	91	3	Pressed Steel Company's Works, Paisley.	Associated Electrical Industries (Manchester), Ltd.
Eastern	North-East London suburban lines:				
	(*a*) Liverpool Street–Enfield–Chingford	52	3	B.R., York	General Electric Company, Ltd.
	(*b*) Liverpool Street–Bishop's Stortford–Hertford East	19	4	B.R., Doncaster	Do.
Eastern	London, Tilbury and Southend (L.T.S.)	112	4	B.R., York and Doncaster ..	English Electric Company, Ltd.
Eastern	Shenfield augmentation stock (S.A.S.)	42	4	B.R., York	English Electric Company, Ltd.
Eastern	Converted stock:				
	(i) Liverpool Street–Shenfield	92 (*a*)	3	Converted at B.R., Stratford ..	Associated Electrical Industries (Manchester), Ltd.
	(ii) Liverpool Street–Shenfield–Southend (Victoria) ..	32 (*b*)	4		
London Midland ..	Crewe–Manchester (also Crewe–Liverpool)	45	4	B.R., Wolverton	Associated Electrical Industries (Rugby), Ltd.

(*a*) The original D.C. equipments were made by the English Electric Company.
(*b*) The original D.C. equipments were made by the General Electric Company, Ltd.

Fig. 1. Multiple Unit—General Layout of Electrical Equipment



Section IV. The Multiple-Unit Trains

General

53. A general description of the multiple-unit trains is given in this section. The descriptions are of the equipment *as originally supplied* unless otherwise stated.

Composition of units

54. The trains are made up of 3- or 4-car units. A 3-car unit comprises a motor coach with a guard's van at one end, and two driving trailers each with a motorman's compartment at one end. A composite coach is added to make up the 4-car unit.

A feature of the design is that all the main electrical equipment is carried below floor level in the motor coach. Some of the low tension controls are in a compartment of the guard's van which also houses the conservator tank of the transformer oil cooling system. The pantograph, air-blast circuit-breaker and the voltage measuring device of the automatic power control are mounted on the roof of the guard's van. One of the trailers carries the battery and other auxiliary equipment; most of this is also below floor level.

The layout of the Glasgow 3-car unit which is typical is shown by Fig. 3.

The multiple-unit fleets

55. Table 3 gives brief particulars of the various units, the workshops where they were built, and the names of the electrical contractors.

General characteristics and leading particulars

56. The new stock, i.e., all but the stock converted from 1,500 volts D.C. operation, has been built to the same general specification.

The 3-car units have been designed for high density suburban service with frequent stops, and the 4-car units for the faster outer-suburban and similar types of service. The general characteristics of these services have already been given in Table 2.

57. The maximum designed speed is 75 m.p.h. and the rate of acceleration is 1·35 m.p.h./sec. for the 3-car units and 1·1 m.p.h./sec. for the 4-car units. The total continuously rated power of the motors per unit varies between 770 and 840 h.p. and the tractive effort between 6,000 and 7,000 lb. depending on the duty.

58. The trains are equipped throughout with Westinghouse electro-pneumatic and automatic air brakes. The main air reservoir also supplies compressed air for the auxiliaries, such as the pantograph motor and the air-blast for the main circuit-breaker. This air supply is supplemented by an auxiliary compressor taking power from the battery; it is used to provide air for raising the pantograph when no air is available from the main supply.

The electrical equipment

59. The pantograph, the circuit-breaker, the automatic power control (A.P.C.), the driver's controls and the lighting, heating and braking equipments are all virtually the same for each type of unit. There are two makes of main circuit-breaker and some differences in the details of the A.P.C. and other auxiliary equipment. The power circuits, transformers, rectifiers and motors vary according to the contractor concerned. The general layout of the equipment is shown diagrammatically by Fig. 1.

The pantograph

60. The same type is used throughout. It is a British modification of a French design. It consists of a single air-operated spring-controlled member which is raised by admitting air to a motor that overcomes the force of the holding-down springs. It is designed to work with the overhead conductors at heights varying between 13 ft. 5 in. under low bridges with a clearance of only 4 ins. between the conductor and the moving loads on the 6·25 kV sections and a maximum of 20 ft. above rail level. The standard height of the conductor is 16 ft. The pressure between the pantograph and the conductor is of the order of 18 to 20 lb.

The air-blast circuit-breaker (A.B.B.)

61. There are two types of air-blast circuit-breaker—

(*a*) the Brown Boveri type;

(*b*) the A.E.I. type.

The former is used throughout the multiple-unit fleet except for 12 units of the Glasgow stock and 124 units of the converted stock which are equipped with the A.E.I. type.

62. Both circuit-breakers operate on the same principle. Each comprises an arc extinction chamber housing the main contacts and an isolating switch. The main contact is opened at high speed under air pressure which also extinguishes the arc that is formed, after which the air operated isolating switch opens, thereby completing the operation; the main contact then recloses. The breaker is closed by operating the isolating switch only, the main contacts in the arc extinction chamber remaining closed.

63. The A.B.Bs. are very rapid in their action and considerable over-voltages are generated when they open the highly inductive circuits which they control. These over-voltages are governed by the combined characteristics of the breaker and the circuit which is being opened, but are substantially the same whether they are operated on 25 or 6·25 kV so far as the primary circuit is concerned, but the voltage peaks on the secondary circuit when operating on 6·25 kV are about four times greater than when operating on 25 kV. The Brown Boveri circuit-breaker is provided with a shunting resistance across the air-blast contact.

64. The control circuits of both breakers include a governor to open the breaker should the air pressure fall so low that it would not give a strong enough blast for arc extinction under fault conditions. The Brown Boveri breaker also had a lock-in mechanism which was intended to prevent this. Its setting was intended to be even lower than that of the opening device in the control circuit, but this setting was found to be unreliable and the device has been removed.

Automatic power control (A.P.C.)

65. As already explained the 25 kV and the 6·25 kV sections of the overhead equipment are separated by neutral sections and the automatic changeover from one voltage to the other is initiated by permanent magnet inductors fixed to the track.

Each motor coach carries a receiver which responds to the magnetic field of the ground magnet. On passing over the first inductor the receiver operates a relay which opens the A.B.B. before the pantograph reaches the neutral section, and on passing over the second inductor (beyond the neutral section) the receiver operates another relay which releases the lock on the circuit-breaker so that it can be closed by the voltage selection equipment.

This equipment comprises voltage sensing apparatus on the roof which receives current directly from the pantograph and feeds it to a group of selector relays which control the operation of the changeover switch. A more detailed general description of this equipment as developed by A.E.I. (Manchester) for the Glasgow units and the modifications made to it are given in paragraphs 141 to 146.

Motor control circuits

66. The operation of the D.C. traction motors on all multiple-units except the converted stock is controlled by varying the voltage from the transformers by means of taps on the secondary windings. The converted units have retained the original D.C. circuits, and motor voltage is controlled by varying the circuits and cutting out successive steps of starting resistance during acceleration in accordance with normal D.C. practice.

Main power circuits

67. The arrangements of the main power circuits vary widely. They are shown by the schematic diagrams in Fig. 4, and the chief differences are summarised in Table 4.

Table 4. The multiple-units. Comparison of power circuits

Type of unit	Main circuit	Number and type of rectifier	Motor connections	Earth point	Voltage control
Scottish Region Glasgow, A.E.I., Manchester	Two parallel pairs of motors, each pair being fed by its own pair of push-pull rectifiers from the centre-tapped transformer secondary winding.	4 mercury arc ..	Parallel	Mid-point of secondary winding and each motor field winding.	Intermediate taps on each half of the secondary winding and a mid-point. Switch sequence outwards from the mid-point alternately on one and then on to the other half of the winding. Field weakening in one stage.
Eastern Region G.E.C.	Two circuits each through a group of 4 bridge-connected rectifiers to a pair of motors in series. An equalising connection between the mid-point of each pair of motors.	8 mercury arc ..	Two series–pairs in parallel.	Mid-point of transformer secondary.	Taps throughout the secondary winding. Switching sequence through consecutive taps. Field weakening in two stages.
Eastern Region English Electric L.T.S. stock	Two circuits each through a pair of bi-phase connected rectifiers to a pair of motors in series. An equalising connection between the mid-point of each pair of motors.	4 mercury arc ..	Do.	Mid-point of motor circuit.	Bi-phase secondary windings each in two parts—one with and the other without tappings. Tapped portions used twice, first in series with reactors and secondly in series with untapped portions. Field weakening is in one stage.
Eastern Region English Electric Shenfield augmentation stock.	Single circuit through bi-phase connected rectifiers to 2 pairs of series-connected motors in parallel.	2 arms of 6 strings each with 16 silicon cells (*a*) in series.	Do.	Do.	Do.
Eastern Region Converted stock, A.E.I., Manchester	Single circuit through bridge connected rectifiers to 4 original resistance-controlled motors.	4 arms of 6 strings each with 11 germanium cells in series.	Conventional D.C. series–parallel control.	Motor circuit (negative end).	Standard D.C. control by cutting out successive steps of starting resistance, first in series and then in parallel and then using weak field connections.
London Midland Region A.E.I., Rugby	Single circuit through bridge connected rectifiers to 4 motors in parallel.	4 arms of 10 strings each with 12 germanium cells in series.	Parallel	Both motor and transformer secondary circuits earthed.	Taps on one half of the secondary winding. Voltage control used tapped and untapped portions of the windings; first in opposition then with the untapped portion only in circuit and finally with the tapped portion boosting the other. Field weakening in two stages.

(*a*) The sub-contractors for the silicon cells are the Westinghouse Brake and Signal Company.

The transformer

68. All the units have a main transformer with a primary winding made up of four equal sections and an electro-pneumatic changeover switch which connects these sections either in series or in parallel according to the line voltage. The arrangement of the secondary winding varies according to the method of tap changing used for motor voltage control, as summarised briefly in Table 4.

The capacities and voltages of the various transformers are given in Table 5. The values refer to 25 kV.

Table 5. The multiple-unit transformers

Capacity and voltages

Region	Manufacturer	Primary		Secondary	Tertiary
		kV	kVA	Volts	Volts
Scottish (Glasgow)	A.E.I., Manchester	25/6·25	970	2770	273
Eastern	G.E.C.	25/6·25	1000	1870	269
Eastern (L.T.S. stock and Shenfield augmentation stock)	English Electric ..	25/6·25	990	1875	284
Eastern (Converted stock)	A.E.I., Manchester	25/6·25	895	1900	269 (1956) or 140/269 (1949)
London Midland	A.E.I., Rugby ..	25/6·25	945	1400	267

69. The transformer is oil-cooled and is mounted between the main members of the underframe in the centre of the motor coach except in the A.E.I. Rugby units where it is mounted in a side bay.

Variations in oil volume on account of changing temperature are taken up in a conservator tank mounted in the equipment compartment of the guard's van. All the systems, except for the Glasgow transformers, work under positive pressure.

70. The designs of the transformers varied considerably and they are summarised in Table 6.

Table 6. The multiple-unit transformers. Summarised description

Type	Description
Scottish Region: Glasgow units A.E.I., Manchester	Three-limb core with axes horizontal. Coils on centre limb. Primary: pancake winding wound in four sections outside the secondary winding. Secondary: helical winding of eight sections in five layers laid one on top of the other; cooling ducts between the core and layer 1, between layers 2 and 3 and between layer 5 and the primary winding. Tertiary: two coils in parallel, one at each end of the primary.
Eastern Region: G.E.C. units	Two-limb core with the coil axes horizontal and two sets of coils in parallel, one on each limb. Tertiary winding is next to the core, then the secondary in two layers and finally the primary which is a disc type and wound in two sections axially disposed. Cooling ducts are between the tertiary and secondary windings, between the two layers of the secondary, and between the secondary and primary windings.
Eastern Region: English Electric units (L.T.S. stock and Shenfield augmentation stock)	Three-limb core with axes horizontal. Pancake windings on centre limb. Primary and secondary interleaved; tertiary coils at each end. The spaces between the coils form the oil-cooling ducts.
Eastern Region: (Converted stock) A.E.I., Manchester	Three-limb core with axes horizontal. Coils on centre limb. The secondary is wound in two layers and the primary is wound on the outside on to a hard board cylinder between it and the secondary. The tertiary is centrally wound between layers of the primary. There are oil ducts between the layers of the secondary and between it and the primary with radial ducts at suitable points.
London Midland Region: A.E.I. Rugby units	Two-limb core with coil axes horizontal. Similar to the G.E.C. transformer in general design, but construction differs in detail.

The rectifier

71. The rectifiers also vary greatly in design and the chief features are summarised in Table 7.

Table 7. The multiple-unit rectifiers

Unit	Description of rectifier		
	Number	Type	Cooling system
Glasgow: A.E.I., Manchester	4	Single anode pumpless steel tank mercury arc. Excitron type.	Air cooled.
Eastern Region: G.E.C.	8	Do.	Liquid cooled.
Eastern Region: English Electric (L.T.S. stock)	4	Do.	Air cooled.
Eastern Region: English Electric, Shenfield (Augmentation stock)	—	Silicon semi-conductor, two arms of 6 strings each in parallel. Each string with 16 cells in series. Total 192 cells.	Air cooled.
Eastern Region: A.E.I., Manchester (Converted stock)	—	Germanium semi-conductor, four arms of 6 strings each in parallel. Each string with 11 cells in series. Total 264 cells.	Air cooled.
London Midland Region: A.E.I., Rugby	—	Germanium semi-conductor, four arms of 10 strings each in parallel. Each string with 12 cells in series. Total 480 cells.	Air cooled.

The traction motor

72. There are four traction motors per motor coach, one per axle, and they are axle-hung with rubber resilient nose suspension. They operate on D.C. with a 30 per cent. ripple at continuous rating, except the English Electric motors which are designed to withstand a 40 per cent. ripple. The amount of ripple is controlled by the size of the choke in series with the traction motors.

73. The rated continuous capacity in weak field of the various traction motors is given in Table 8. The motor voltage was selected with due regard to the type of rectifier to give the best combination for both motors and rectifiers.

Table 8. The multiple-unit traction motors. Rated capacity in weak field

Region	Manufacturer		H.P.	Volts	Amps
Scotland (Glasgow) ..	A.E.I., Manchester		210	975	180
Eastern	G.E.C.		200	693	240
Eastern	English Electric		192	620	250
Eastern (Converted stock)	English Electric (*a*)	1949	157	675	195
	G.E.C. (*a*)	1956	174	675	214
London Midland ..	A.E.I., Rugby		210	975	180

Note: (*a*) A.C. equipment supplied by A.E.I. (Manchester).

The auxiliaries

74. The auxiliaries generally are very similar on each type of unit. The power for them is drawn from the tertiary winding of the main transformer at 240 volts nominal. This A.C. supply is used for the train heating, the battery charger, the main air compressor and for all auxiliary motors that are not required when the line voltage is off.

The fan motors and oil pump motors are single phase induction capacitor start and run machines. The main compressor for the brake system is a Westinghouse Type CM38 with a D.C. series motor supplied through a rectifier bridge. Battery chargers are of the static type taking A.C. through transductor regulated rectifiers. These are selenium rectifiers, except in the A.E.I. equipments which have germanium cells.

The battery charger charges a 110-volt battery which supplies power for the control circuits, for the lighting and for those auxiliaries that are required to remain when the line voltage is off, including the auxiliary compressor used for charging the air reservoir for working the pantograph and the A.B.B.

Protection

75. The protective arrangements for the different units vary to some extent. They are summarised briefly in Table 9.

Table 9. The multiple-units. Protective arrangements

	Scottish Region A.E.I. (Manchester)	Eastern Region				London Midland Region A.E.I. (Rugby)
		G.E.C.	E.E.		Converted stock	
			L.T.S.	S.A.S.		
I. *Traction Motors*						
Overcurrent	Yes	Yes	Yes	Yes	Yes	Yes
Earth fault	Yes	No	Yes	Yes	No	Yes
II. *Rectifiers*						
Under-temperature	Yes	Yes	Yes	No	No	No
Over-temperature	No	Yes	Yes	No	No	No
Backfire	Yes	(*b*)	Yes	(*a*)	(*a*)	(*a*)
Failure of excitation	Yes	No	Yes	(*a*)	(*a*)	(*a*)
Air flow	No	(*a*)	No	Yes	Yes	Yes
III. *Transformers*						
Primary overload	No	Yes	Yes	Yes	No	Yes
Primary differential relay	Yes	No	No	No	Yes	No
Secondary overload	Yes	(*b*)	Yes	Yes	Yes	No
Secondary earth fault	Yes	(*b*)	Yes	Yes	No	Yes
Gas relay	No	No	No	No	No	No
Oil level	Yes	Yes	Yes	Yes	Yes	Yes
Oil flow	Yes	No	No	No	Yes	No
Over-temperature	Yes	Yes	Yes	Yes	Yes	Yes

(*a*) Not applicable.

(*b*) Faults in the secondary circuit open the primary overload relay.

Section V. The A.C. Locomotives

76. For the first stage of the Euston–Crewe–Manchester–Liverpool electrification 100 dual voltage A.C. locomotives were ordered to a common specification. Brief particulars of the fleets are given in Table 10.

Delivery began in October, 1959, and by 31st December, 1961, all were delivered except 33 still being built at the British Railways' Doncaster Works. They had run by that date for 160,000 miles on trial running and for over 800,000 miles hauling express passenger and freight trains between Crewe and Manchester.

77. The specification called for a mixed traffic Bo-Bo locomotive capable, among other duties, of hauling between London and Manchester—

a 475-ton express passenger train at an average speed of 67 m.p.h. with a balancing speed of 90 m.p.h. on level track and a maximum of 100 m.p.h.,

or

a 950-ton freight train at an average speed of 42 m.p.h. with a maximum of 55 m.p.h.

Five locomotives were ordered to the same specification but with a different gear ratio to enable them to haul a 1,250-ton freight train at the same average speed of 42 m.p.h.

The maximum weight was limited to 80 tons, equally divided over the four axles.

Table 10. The London Midland Region A.C. Locomotives

Electrical Contractor	Mechanical parts built by	Weight Tons	B.S. ratings HP Cont : W.F.	Number of locomotives ordered
A.E.I. (Manchester), Ltd. ..	Beyer Peacock, Ltd.	78·4	3310	10
A.E.I. (Rugby), Ltd.	Birmingham Railway Carriage and Wagon Company, Ltd.	80·0	3200	25
A.E.I. (Rugby), Ltd.	British Railways Doncaster Locomotive Works.	79·0	3200	40
G.E.C., Ltd.	North British Locomotive Company, Ltd.	77·0	3080	10
English Electric Company, Ltd.	Vulcan Foundry, Ltd.	73·0	2950	15

Electrical features

78. The Contractors were given wide scope in their choice of electrical equipment, and this led to several contrasting designs. The 40 equipments for locomotives built or building at Doncaster have semi-conductor rectifiers, the others have mercury arc rectifiers. The English Electric rectifiers are of the ignitron type, the others are excitrons. Two types control the traction motor voltage by tappings on the transformer primary winding, and the other three have tappings on the secondary windings. The type with semi-conductor rectifiers have a rheostatic brake in addition to the air/vacuum brake which is standard throughout the fleet.

It is not necessary for the purpose of this investigation to describe the equipment in detail, but a brief summary of the main electrical features is given in Table 12, and simplified power circuit diagrams are shown by Fig. 5.

Protection

79. The protection provided is comprehensive and it is summarised very briefly in Table 11.

Table 11. The A.C. locomotives. Protective arrangements

	A.E.I., Manchester	A.E.I., Rugby	B.R./ A.E.I.	G.E.C.	E.E. Company
A. *Direct protection*					
I. TRACTION MOTORS					
Overcurrent	Yes	Yes	Yes	Yes	Yes
II. RECTIFIERS					
Overload	Yes	Yes	Yes	No	Yes
Under-temperature	Yes	Yes	No	Yes	Yes
Over-temperature	Yes	Yes	Yes	Yes	Yes
III. TRANSFORMERS					
Power-Regulating Tapping System..	Primary Taps	Secondary Taps	Secondary Taps	Primary Taps	Secondary Taps
Primary overload	No	No	No	Yes	No
Primary differential protection ..	Yes	No	No	No	No
Secondary overload	Yes	Yes	No	No	No
Secondary earth-fault	Yes	Yes	Yes	Yes	Yes
Gas relay (Fast or 2nd stage) ..	No	Yes	Yes	Yes	Yes
Oil level	Yes	Yes	No	Yes	No
Oil flow	Yes	No	No	Yes	No
Over-temperature (2nd stage) ..	No	No	Yes	No	Yes
B. *Indicators only*					
I. TRACTION MOTORS					
Blower failure	Yes	Yes	Yes	Yes	Yes
II. RECTIFIERS					
Backfire	Yes	Yes	No	No	No
Fan failure	Yes	Yes	Yes	No	No
III. TRANSFORMERS					
Gas relay (Slow or 1st stage) ..	No	Yes	Yes	No	Yes
Over-temperature (1st stage) ..	No	Yes	Yes	No	No
Fan failure	Yes	No	No	No	No
Oil flow	No	No	No	No	Yes

Table 12. The A.C. Locomotives. Electrical Features

Electrical contractor	Traction motor voltage control	Rectifier and traction motor power circuits	Voltage changeover 25/6·25 kV	Transformers	Rectifiers	Traction motors
A.E.I., Manchester..	H.V. tap changer on auto-transformer feeding into a fixed ratio rectifier transformer. Tap changer has 40 taps.	Secondary of rectifier transformer feeds rectifiers in bi-phase. 4 traction motors in parallel. Earth on motor circuit.	Tappings on the primary winding for either 25 kV or 6·25 kV.	Main auto-transformer and double winding step-down (secondary transformer) built together on a partially common core. Oil-cooled.	3, 6-anode excitron air-cooled, pumpless, steel tank, mercury arc.	4, 6-pole, with interpoles and lap-wound armatures; mounted on the bogie frame, 3-point suspension, Alsthom flexible drive: gear ratio 29/76.
A.E.I., Rugby ..	L.V. tap changer on part of secondary bucking and boosting two fixed ratio portions of the secondary winding. The nett output is taken through a fixed ratio auto-transformer to the rectifiers.	Auto-transformer feeds rectifiers in bi-phase. 4 traction motors in parallel. Earth on motor circuit.	Primary in 4 sections connected in series for 25 kV and in parallel for 6·25 kV.	Primary and secondary winding of main transformer wound on one core, oil-cooled, with the separate auxiliary auto-transformer air-cooled.	Do.	Do.
A.E.I., Rugby (B.R. built).	Do.	Auto-transformer feeds rectifiers in bridge connection. 4 traction motors in parallel. Earth on motor circuit.	Do.	Do.	30 locos with germanium semi-conductors: 4 arms each of 8 cells in series and 40 strings in parallel. 10 locos with silicon semi-conductors: 4 arms each of 7 cells in series and 12 strings in parallel.	Do.
The General Electric Company, Ltd.	H.V. tap changer on auto-transformer feeding into a fixed ratio rectifier transformer with two secondary windings. Tap changer has 40 taps, 20 of which are intermediate steps using series resistance.	Two secondaries of rectifier transformer in parallel feed two groups of bridge-connected rectifiers, each group of rectifiers supplying two traction motors in series, but effectively in parallel. Earth on motor circuit.	Tapping on the primary winding for either 25 kV or 6·25 kV.	3 cores: one outer leg carries the regulating auto-transformer winding and the auxiliary winding: the other outer leg carries the two parts of the secondary winding: the centre leg carries a flux difference between the others. Oil-cooled.	16 single anode excitron liquid-cooled pumpless steel tank, mercury arc of the Com-pak type, similar but larger than those on the M.Us.	4, 6-pole with interpoles compensating winding and lap-wound armatures; mounted on the bogie frame, 3-point suspension, Brown Boveri flexible drive; gear ratio 25/74.
The English Electric Company, Ltd.	L.V. tap changer on part of each half of secondary, each tap changer part boosted by a fixed ratio portion of the secondary winding connected in series.	Whole of secondary winding feeds two groups of bridge-connected rectifiers in parallel, each group of rectifiers supplying two traction motors in series, but effectively in parallel. Earth on motor circuit.	Primary in 4 sections connected in series for 25 kV and parallel for 6·25 kV.	Shell type with groups of interleaved windings: oil-cooled.	8 single anode ignitron liqnd-cooled pumpless steel tank, mercury arc.	4, 4-pole with interpoles and lap-wound armatures; mounted on the bogie frame 4-point suspension, SLM–Brown Boveri flexible drive; gear ratio 25/76.

Summary of the electrified routes

80. Before recording the results achieved in trial running, I give below a summary of the routes used for that purpose and the units that were tested on them:

(*a*) *The Lancaster–Morecambe–Heysham line.* Reopened for A.C. electric traction but at 50 cycles in November, 1952. Energised throughout at the single voltage of 6·6 kV.

This line was used for the early experiments, primarily with equipment supplied by the English Electric Company, but later with an M.V.E., now A.E.I. (Manchester) unit.

(*b*) *The Styal line.* Brought into use in October, 1958. Energised throughout at the single voltage of 25 kV.

This line was used for testing the first experimental A.C. locomotive, the first English Electric units, and the first of the Glasgow units. After this the London Midland Region multiple-units and A.C. locomotives were commissioned and tested on this line and on the main Crewe–Manchester lines when they were ready.

(*c*) *The Colchester–Clacton–Walton line.* Brought into use in February, 1959. This is also a 25 kV line but a short section could be energised at 6·25 kV for testing the voltage changeover equipment of individual units.

This line was the main testing ground for the English Electric and G.E.C. units, most of which were commissioned there. The line was also used for testing the converted stock.

(*d*) *The Glasgow suburban lines.* The Milngavie branch, energised at 6·25 kV, was opened for testing in July, 1959, the first voltage changeover point was ready in September, 1959, a comprehensive section of 6·25/25 kV lines with voltage changeover points was ready by March, 1960, and all the lines were electrified by September, 1960.

These lines were used for the commissioning and testing of the A.E.I. (Manchester) units, though the first units to be tested were English Electric sets destined for the L.T.S. line.

(*e*) *The North-East London suburban lines.* The Hertford East branch energised at 25 kV was ready by May, 1960, but the first 6·25 kV line was not brought into use until September, 1960. These lines were used for the final testing of the G.E.C. units.

The Glasgow (A.E.I. Manchester) multiple-units

A.E.I. Experiments on the Lancaster–Morecambe–Heysham line

81. In 1956 the M.V.E. Company (now A.E.I. Manchester) equipped a 3-car unit for experimental use on the Lancaster–Morecambe line. This was used to gain experience with A.C. traction, and during its trials various modifications were made to the rectifiers, control gear, etc.

The unit ran for 142,000 miles between April, 1956, and 31st January, 1960. The rectifiers in service at the latter date had run for 100,000 miles and they were similar to those supplied for the Glasgow units. This unit is still in operation and is giving excellent service.

Testing on the Styal line

82. On 18th June, 1959, the first 3-car unit for the Glasgow suburban service was commissioned on the Styal line and it ran there for 6,700 miles before it was returned to the Scottish Region on 22nd March, 1960. This prototype unit was equipped by A.E.I. (Manchester) with the same type of components as those used in the Glasgow units.

During this period no troubles were experienced with the transformer, the rectifiers or motors, all of which appeared to function excellently. There were no troubles from voltage surges and the main power circuit required no modifications. On some occasions the air-blast circuit-breaker failed to reset after passing through the neutral section and these faults were traced to the automatic power control equipment for voltage selection, and some modifications were made to the relays. Some faults appeared in the motor control equipment also and modifications were made to the tap changers.

Trial running on the Glasgow suburban lines

83. On 12th July, 1959, the Milngavie branch, energised at 6·25 kV, was opened for trial running but the first unit to be tested was an English Electric set destined for the L.T.S. line. The first A.E.I. unit began trials in September, 1959, and by mid-May, 1960, 30 units had been commissioned and were being given periodical trials. When the public services opened on 5th November, 64 units had been commissioned.

At the same time as the units were undergoing trials, the electrification of the line was being extended. The voltage changeover neutral section at Westerton was ready early in September, 1959, and by March, 1960, the voltage changeover neutral section near Dalmuir Park was also in use. By the end of May, 1960, the lines from Westerton to Balloch and from Dalmuir Park to Garscadden were available for trial running as well as the Milngavie branch.

84. Much of the equipment gave excellent service. There was not a single breakdown of a traction motor; some minor troubles were experienced with the transformers and their thermostats, and on two occasions the changeover switch did not function correctly. A few rectifiers failed, but the most constant feature was the operation of the overload relays, probably as a result of rectifier backfires, whilst fuses were blown in the tertiary circuit on a number of occasions.

85. The full significance of the last two types of failure mentioned above were not appreciated at the time. It should be remembered, however, that not only were new lines being equipped and new trains tested, but motormen were being trained in their operation and the depot staff in their maintenance. Contractors' staff were also unfamiliar with the traction equipment, some of which was of novel design and comprised features never before used on any electrified railway, namely, the automatic power control and the voltage changeover.

In these circumstances troubles of varying degree were to be expected and assisted running was a fairly common occurrence, and drivers frequently had to reclose circuit-breakers following the operation of protective devices.

During this period up to the opening of public services on 5th November, 1960, the mileage run on trials and during commissioning was 183,400 miles.

The North-East London (G.E.C.) units

Trials on the Colchester–Clacton–Walton lines

86. The first 4-car unit with the G.E.C. prototype equipment installed in motor coach No. 501 began trial running on the Colchester–Clacton–Walton lines on 28th October, 1959. This coach ran for 14,600 miles up to 21st March, 1960, when it was returned to Ilford car shed for exchanging the prototype motors for the production types. Some changes were made in control gear but the service records show few failures during these five months.

The coach was returned to passenger service on 5th May, 1960, and ran for a further 10,900 miles until 14th July, when it was withdrawn for the replacement of all the prototype equipment by production types. There was one rectifier cylinder and one tap changer failure during this period. Altogether this unit ran for 25,500 miles without developing any faults which were thought to be serious.

Commissioning and trial running of the service units on the Colchester–Clacton line 13th April to 28th December, 1960

87. As further G.E.C. units were completed in the Railway Workshops at York and Doncaster they were taken to the Colchester–Clacton line for commissioning, trial running and the training of motormen. All the 71 units of the fleet were tested for varying periods between 13th April and 28th December, 1960. During this period the failures of 14 rectifier cylinders and two battery chargers were reported. The total mileage run during commissioning and testing on this line was 37,100 miles.

Trial running on the North-East London suburban lines

88. Trial running and the training of motormen on these lines began on 23rd May, 1960, when the overhead equipment between Rye House and Hertford East was energised at 25 kV. As further sections of the overhead equipment were completed, trial running was extended towards London. The first 6·25 kV section between Cheshunt and Hackney Downs was brought into use on 30th September, 1960, and by 4th November all the N.E. London lines were ready for the opening of the complete electrified service.

By this date 54 units, excluding the prototype coach No. 501, had been commissioned and run for a total of 50,400 miles—but almost entirely on the 25kV sections of the line—the other 16 units were commissioned and tested on the Colchester–Clacton lines and sent from there direct into service after the public opening of the North-East London electrification.

As the regular passenger services had to be maintained, trial running was confined to restricted periods and only 22 units were continuously in operation. The others ran for about 200 miles and then were stabled in sidings to await the introduction of the public electric services.

89. During this period there were some rectifier failures, but on examination no defects could be found and there were five failures of battery chargers. No serious trouble was experienced with the control gear, but the tripping of overload relays was a fairly constant feature. Investigation of the blowing of tertiary fuses which was becoming a regular occurrence led to the examination of the transformers as described in paragraph 207 and to the modification of all of them before public services began on the North-East London lines.

There were no transformer failures in service, nor were there any traction motor failures, though one was withdrawn from service on account of accidental damage.

90. The troubles up to this date were still considered to be of a transitory character. It was believed that cures had been found for all of the known defects, and it was decided to adhere to the planned dates for the introduction of the public services.

It will be appreciated that the traffic conditions under which the G.E.C. units were tested were very similar to those on the Glasgow suburban lines. A heavy steam suburban passenger service had to be maintained, and motormen and depot staff had to be trained in the operation and maintenance of the new equipment; Contractors' staff were also unfamiliar with it.

The L.T.S. and Shenfield augmentation (English Electric) units

The initial experiments on the Lancaster–Morecambe–Heysham line

91. As already mentioned trial running of the first A.C. electric units operating at the commercial frequency of 50 cycles began in November 1952. Three 3-car units, originally used on the 4th rail D.C. system of the Willesden–Earls Court line, were converted at the Wolverton Works of the London Midland Region and fitted with A.C. equipment by the English Electric Company. Components readily available were used and the transformers, rectifiers and most of the switchgear were mounted above floor level where they could be easily examined. They were not representative of the present equipment which is attached to the underframe below floor level.

Power from the overhead line was collected by the pantograph in the usual way and fed to the transformers through a 6·6 kV fuse instead of an air-blast circuit-breaker. The transformer comprised a single wound primary, a secondary in two parts each with tappings for voltage control, and a tertiary for supplying the auxiliaries. There were two air-cooled mercury arc rectifiers each feeding two D.C. traction motors connected in series with the mid-point earthed. The basic circuits were very similar to those on the new English Electric units.

92. The three English Electric 3-car units ran for over 1,000,000 miles between November, 1952, and 31st January, 1960, and they are still maintaining an efficient and trouble free service. During this period no material change was made to the first unit. A new transformer with oil cooled reactors and feeding single anode excitron type rectifiers and with a modified electro-pneumatic contactor control gear was fitted to the second unit in 1955.

During the same year the third unit, after having run for 125,000 miles, was fitted for experimental purposes with germanium type rectifiers supplied by the B.T.H. Company (now A.E.I. Rugby). Some modifications were made to the temperature control arrangements, and for a time the germanium rectifiers were replaced by silicon ones in order to gain experience with these types of semi-conductor which had not previously been used for electric traction.

93. During this period of trial running no troubles were ever encountered with voltage surges and hence no impulse tests were carried out. The basic circuit never gave any serious trouble and consequently tests were mainly related to details of apparatus design and to investigating quantitatively such factors as harmonics, power factor, voltage regulation, etc.

It should be noted, however, that the units were not equipped with circuit-breakers and that the overhead lines were energised at a single voltage.

Trial running on the Styal line

94. When the Styal line was opened for trial running on 26th October, 1958, the first multiple-units to be tested were those equipped by the English Electric Company. They were also used for training motormen and maintenance staff in operation and maintenance.

Altogether four units were commissioned on this line, and they ran for 21,600 miles, virtually trouble free. A few modifications were made as was to be expected with new equipment, but nothing fundamental.

Trial running on the Glasgow suburban lines

95. On 12th July, 1959 an English Electric 4-car unit, destined for the L.T.S. line, began trial running on the Milngavie branch and it was also used for training motormen. In October, 1959, 3 more L.T.S. units arrived primarily to assist with the training of motormen until such time as sufficient A.E.I. units were available.

The four L.T.S. units were eventually despatched to the Eastern Region in February, 1960, having run altogether for some 7,500 miles. Their performance had been very satisfactory and there were only a few minor troubles.

Trial running and commissioning on the Colchester–Clacton–Walton lines

96. The first English Electric 4-car unit destined for the L.T.S. line began trial running in February 1959 and six weeks later a passenger service was started. During the period February 1959 to October 1960, 112 units were commissioned and tested. The four units from the Styal line were transferred during the summer of 1960 for stabling and final checking before entering public service. Most of the other units were also stabled in sidings and brought into use in turn to keep them all in a serviceable condition. A few were retained in continuous service to test the reliability of the equipment. Altogether 175,400 miles were run during commissioning and testing. Some of these units were sent to augment the new A.C. service on the Liverpool Street–Southend (Victoria) lines when these were converted in November, 1960 and in December, 1960 others were used to replace G.E.C. units on the North-East London suburban lines.

97. The additional fleet of English Electric units now operating on the Liverpool Street–Chelmsford–Southend (Victoria) services (the Shenfield augmentation stock) have also been tested on this line. The electrical equipment is very similar in design to the early stock destined for the London, Tilbury and Southend services, but silicon semi-conductors have been provided in place of mercury arc rectifiers. These units had run for 54,100 miles on trial up to 31st December, 1961, and after completing satisfactory tests they were transferred to the Liverpool Street–Chelmsford–Southend (Victoria) services where they are operating very successfully. Eight units are now in service on the recently electrified London, Tilbury and Southend lines.

The converted stock

98. Some of the converted stock was also tested on the Colchester–Clacton–Walton lines primarily to check the operation of the automatic power control equipment and the working of the original D.C. equipment with power supplied from the A.C. transformers. No difficulties of any significance were experienced. The other units have been tested on the Liverpool Street–Shenfield–Chelmsford route. They have run altogether for some 29,100 miles on tests.

The London Midland Region multiple-units and A.C. locomotives

Multiple-units

99. The first unit began trial running on the Styal line on 23rd April, 1960, and by the time the public services between Crewe and Manchester, including the Styal line, were opened on 12th September, 15 units were available and these had run on trial for 20,600 miles. Up to 31st December, 1961, another 30 units had been delivered and 38 in all had been commissioned. These included units for the recently opened Crewe–Liverpool electrified lines. Up to 31st December, 1961, the multiple-unit fleet had run for nearly 41,000 miles on trial.

Three units were loaned to the Eastern Region from 12th December, 1960. Up to the end of April they were running on the Liverpool Street–Southend (Victoria) and Shenfield–Chelmsford lines, the whole of which is energised at 6·25 kV and since then have been working on the Liverpool Street and Hertford East–Bishop's Stortford lines which are energised partly at 6·25 kV and partly at 25 kV. The mileage run on the Eastern Region has been 195,000 miles up to 31st December, 1961. One of these units has now been returned to the London Midland Region.

A.C. locomotives

100. The first A.C. locomotive to be tested was an experimental unit with A.E.I. (Manchester) equipment which began running on the Styal line in October, 1958. The A.C. locomotive fleet has been tested partly on this line and partly on the main line between Crewe and Manchester; up to 31st December they had run 160,000 miles on trial.

Summary of trial and service running

101. In order to appreciate the extent of the trial running carried out prior to the opening of public services, I give a time-table of the chief events in Table 13 and a summary of trial and service running up to 31st December, 1961, in Table 14.

Table 13. Trial and service running. Time-table

Date	Event
November, 1952 ..	Experimental English Electric units began tests on the Lancaster–Morecambe–Heysham line.
April, 1956	Experimental A.E.I. (Manchester) unit began tests on the Lancaster–Morecambe–Heysham line.
October, 1958 ..	Experimental A.C. locomotive began tests on the Styal line.
October, 1958 ..	First Englisb Electric unit tested on tbe Styal line.
February, 1959 ..	Testing of English Electric units began on the Colcbester–Clacton line.
March, 1959 ..	First public service began on the Colchester–Clacton line.
June, 1959	First Glasgow unit A.E.I. (Manchester) began trial running on tbe Styal line.
July, 1959	Testing of Englisb Electric units began on the first section (6·25 kV) of the Glasgow suburban lines.
September, 1959 ..	First 6·25/25 kV voltage changeover section available on the Glasgow lines and A.E.I. (Manchester) units began trial running.
October, 1959 ..	First G.E.C. unit began trial running on the Colcbester–Clacton line.
March, 1960 ..	Comprehensive section of the Glasgow lines with two voltage changeover points available for testing A.E.I. (Manchester) units.
April, 1960	First London Midland Region unit A.E.I. (Rugby) began trial running on the Styal line.
May, 1960	Testing of G.E.C. units began on the first section (25 kV) of the North-East London suburban lines.
September, 1960 ..	Comprehensive section of North-East London lines witb voltage changeover point available for testing G.E.C. units.
12th September, 1960	Public electric services began on the Crewe–Manchester and Styal lines.
5th November, 1960	Glasgow suburban electric services opened for public use.
7th November, 1960	Liverpool Street–Shenfield–Southend (Victoria) lines converted from 1500 volts D.C. to 6·25 kV A.C. during the week-end.
14th November, 1960	Restricted public service of electric trains opened on the North-East London suburban lines.
21st November, 1960	Full public service of electric trains opened on the North-East London suburban lines.
12th December, 1960	Electric train services on the North-East London suburban lines reduced on account of difficulties with G.E.C. units.
18th December, 1960	Electric train services withdrawn from the Glasgow suburban lines.
20th March, 1961	Shenfield–Chelmsford line converted to 25kV A.C.
12th September, 1961	Full electric train services introduced on the Crewe–Manchester and Styal lines.
1st October, 1961	Electric train services with modified stock resumed on the Glasgow suburban lines.
6th November, 1961	Limited electric train service introduced on the London, Tilbury and Southend line.

Table 14. Summary of Trial and Service Running of A.C. multiple-unit trains and A.C. locomotives up to 31st December, 1961

Type of Unit	TRIAL RUNNING							PUBLIC SERVICE RUNNING						
	Lancaster Morecambe Heysham	Crewe Manchester incl. Styal line	Colchester Clacton Walton	N.E. London Sub.	Ilford Chelmsford	Glasgow Sub.	Total	Crewe Liverpool Manchester	Colchester Clacton Walton	Liverpool St. Shenfield Southend	Shenfield Chelmsford	N.E. London Sub.	Glasgow Sub.	Total
	6·6 kV	25 kV	25 kV	6·25/25 kV		6·25/ 25 kV		25 kV	25 kV	6·25 kV	6·25/25 kV	6·25/25 kV		
	miles	*miles*	*miles*	*miles*	*miles*	*miles*	*miles*	*miles*	*miles*	*miles*	*miles*	*miles*	*miles*	*miles (a)*
Multiple units														
Scottish Region														
A.E.I. (Manchester) Un-Modified.	—	6,700	—	—	—	183,400	190,100	—	—	—	—	—	335,000	335,000
A.E.I. (Manchester) Modified.	—	—	—	—	—	380,000	380,000	—	—	—	—	—	1,037,000	1,037,000
Eastern Region														
G.E.C. standard units	—	—	37,100	50,400	—	—	113,000	—	70,000	—	—	2,360,000	—	2,430,000
G.E.C. prototype units	—	—	25,500											
E.E. L.T.S. stock ..	—	21,600	175,400	—	—	7,500	204,500	—	← 8,336,000 →				—	8,336,000
E.E. Shenfield augmentation stock.	—	—	54,100	—	—	—	54,100	—	← 1,425,000 →			—	—	1,425,000
Converted stock:														
1949 units	—	—	6,400	—	18,400	—	29,100	—	—	← 3,780,000 →		—	—	3,780,000
1956 units	—	—	4,300	—	—	—		—	—	—	—	—	—	—
London Midland Region														
E.E. experimental ..	1,000,000(*b*)	—	—	—	—	—	1,000,000	—	—	—	—	—	—	—
A.E.I. experimental ..	142,000(*b*)	—	—	—	—	—	142,000	—	—	—	—	—	—	—
A.E.I. (Rugby) standard units.	—	40,800	—	—	—	—	40,800	1,037,000	—	← 195,000 (*c*) →			—	1,232,000
Total mileage	1,142,000	69,100	302,800	50,400	18,400	570,900	2,153,600	1,037,000	← 16,166,000 →				1,372,000	18,575,000
A.C. locos.	—	160,000	—	—	—	—	160,000	820,000	—	—	—	—	—	820,000

(*a*) The miles run are unit (3- or 4-car) or locomotive miles.

(*b*) Includes both service and trial running of the English Electric and A.E.I. (Manchester) experimental units up to 1st January, 1960.

(*c*) L.M.R. stock on loan to E.R.

PART III. THE ACCIDENTS AND FAILURES ON THE GLASGOW SUBURBAN ELECTRIFIED LINES

Introduction

102. On 13th January, 1961, I submitted a short interim report on the failures of five transformers in the Glasgow multiple-units. Since then extensive investigations have been made to trace and put right every possible source of trouble, not only to the transformers but to other parts of the equipment. This final report contains a short description of the original failures and the early investigations, and a more detailed account of the further investigations and of the modifications that have been made on the original units. It is divided into the following sections:

Section VII. The Glasgow transformer failures.
Section VIII. The initial investigations into the Glasgow failures.
Section IX. Further investigations and tests of the Glasgow equipment.
Section X. The modified Glasgow trains, their trials and performance.
Section XI. Conclusions and remarks on the Glasgow failures.

Section VII. The Glasgow Transformer Failures

Explosion at Charing Cross, 30th October, 1960. Unit 003

103. The first serious trouble experienced with the transformers on the new Glasgow electric service occurred on Sunday, 30th October, at about 6.27 p.m. On that day a full-scale rehearsal of the week-day public service was being carried out in order to familiarise the staff with the new conditions. There had been similar rehearsals on two previous Sundays and, except for some minor difficulties, everything had gone according to plan.

On 30th October, however, an explosion occurred in the leading guard's van of an empty 6-car train shortly after it had arrived at Charing Cross station. The guard's van was shattered and the partition between it and the passenger compartment was blown in. Fortunately no one was injured. The transformer tank was bulged and the cover was buckled but the cause of the explosion was traced to a mixture of oil vapour and air having been ignited in the equipment chamber, probably by a spark from a contactor in the low tension cupboard. It was found that the transformer secondary winding had been badly burnt and that the heat so generated had converted some of the cooling oil into gas which had found its way through the conservator tank into the equipment chamber in the guard's van. Urgent action was taken to improve the venting arrangements.

Failure near Queen Street, 14th November, 1960. Unit 042

104. On 14th November, whilst a 6-car train from Hyndland was approaching Queen Street station, the driver noticed a loss of power. Further difficulties were experienced all the way to Airdrie and eventually the train was taken out of service at Dalmuir Park on the return journey. The transformer tank had bulged and the cover was sprung, indicating that it had been subjected to severe internal pressure. Again, the secondary winding had been badly burnt but as there was no explosion it was considered that the improved venting had been effective.

Explosion near Renton, 13th December, 1960. Unit 051

105. On 13th December a third transformer failed, and again the secondary winding was badly burnt, but on this occasion there was a serious explosion very similar to that on 30th October. The train in question was the 7.0 a.m. from Balloch Central to Bridgeton Central, comprising two 3-car units. At about 7.9 a.m. shortly after it had left Renton station an explosion shattered the equipment compartment in the rear guard's van. A passenger pulled the communication cord and brought the train promptly to a stand. The guard's compartment was badly damaged and a partition between it and the adjoining passenger compartment was forced in. There was no derailment or fire.

The train carried about 230 passengers, and of these, two sustained serious injury and five suffered slight injury or shock. The guard also was seriously injured. As soon as the train stopped, passengers went for assistance and also informed the driver who took prompt action to protect the train and to report the accident. Police were quickly on the scene, and the first ambulance arrived at 7.30 a.m. The injured passengers were given First Aid and were evacuated to hospital without delay, the last ambulance leaving the scene at 8.0 a.m. The overhead equipment was isolated at 7.40 a.m., the disabled train was drawn back to Alexandria at 10.20 a.m., and normal working was resumed at 11.5 a.m.

Following this explosion, orders were given to improve still further the venting arrangements and to restrict gas or oil flow between the transformer and conservator tank.

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Failure at Carntyne, 14th December, 1960. Unit 031

106. At about 2.45 p.m. on 14th December clouds of smoke were seen pouring from the transformer of a 6-car train as it entered Carntyne station. Tbere was no explosion or fire hut the transformer tank got bot and oil poured out from the cover. The passengers were detrained promptly, the disabled 3-car unit was placed in a siding, and normal services were resumed witbout delay.

Accident near Garrowhill, 17th December, 1960. Unit 014

107. Finally at ahout 1.52 p.m. on Saturday, 17th Decemher, the accident occurred whicb led to the withdrawal of the services. As the 12.45 p.m. 6-car train from Helenshurgh to Airdrie was leaving Garrowhill station a clerk saw white vapour issuing from beneath the rear vehicle, and very soon afterwards the guard, wbo was travelling in the coach next ahead, heard three bangs and saw clouds of smoke coming from underneath his coach. By means of the train telepbone he called to the driver to stop tbe train. The driver ran back with a fire extinguisher and quickly put out a small fire in the transformer from which the smoke was issuing. Tbe guard went to a nearby signal telephone and advised the signalman who in turn advised the Station Master at Easterhouse. The damaged unit was isolated and the train was worked forward to Easterhouse at 2.10 p.m. wbere the passengers numhering about 250 were detrained. No one was injured. As a precaution the fire brigade was called at 2.11 p.m. and it arrived at 2.23 p.m. Four minutes later the firemen were satisfied there was no fire thougb some smouldering material was damped out with the aid of an extinguisher. The damaged set was then removed to Heatheryknowe Loop, and at 2.50 p.m. normal working on both lines was resumed. It was found that the cover of the transformer had been hurst open and was hanging down close to the track.

Section VIII. The Initial Investigation into the Glasgow Failures

108. Investigations into the causes of the transformer failures hegan immediately after tbe first explosion on 30th October. Tbe transformer was removed from its tank and it was found that the primary winding was in good condition, hut the secondary had heen severely burnt. Some of the copper turns had fused and the layers of coils were badly distorted.

It was thought that the damage might have heen caused hy a failure of the oil circulating system whicb resulted in such severe overheating that the insulation was hurnt and eventually failed and so caused tbe breakdown of the winding.

Examination of the conservator tank showed that the exit from the vent pipe was restricted hy the silica-gel hreather to such an extent that gas pressure built up inside the tank, lifted its lid and so allowed gas to escape into the equipment chamher. Immediate action was taken to change the arrangements by fitting a larger vent pipe and hy-passing the breather.

109. The transformer which failed on 14tb Novemher showed the same signs of damage, and it was concluded that this too had been overheated. This transformer and four others, selected on account of the different treatments they had received in service, were sent to the Wythenshawe Works of Messrs. A.E.I. (Manchester), for further examination. As a result, it was agreed unanimously that the complete disappearance of the secondary insulation on both the failed transformers and tbe absence of any sign of overbeating or damage to the other four, indicated that the failures were due to prolonged overheating of the paper insulation, and almost certainly arose from a failure of the oil circulation around the secondary winding.

110. Arrangements were made to test the oil circulation under various conditions, especially as part of the system worked under a negative pressure, though the oil passing through the transformer tank itself was under a slight positive pressure.

None of these tests indicated that this method of oil cooling was responsible for the overheating and its cause bad not been resolved when the explosion occurred on 13tb December, followed hy the failure on the 14th and the accident on tbe 17th December.

111. On Sunday, 18th Decemher, an important meeting was held at the British Transport Commission Headquarters at which senior officers of tbe Commission discussed the prohlem with representatives of the three manufacturers who had huilt transformers for multiple-units. Possible causes of overbeating were discussed, and it was decided to continue the investigations at Wythenshawe where all the damaged transformers were available for examination.

During an interval in the meeting I discussed with the Commission's officers the desirability of appointing a Consulting Engineer to make an independent investigation, and Mr. F. J. Lane was asked to undertake this work.

112. On 21st December all five transformers which had failed in service were examined; none of the primary windings was damaged, but four of the secondary windings appeared to have been extensively overheated. (Units Nos. 003, 042, 051 and 014.) The paper insulation had been completely burnt off the outer layers, some of the turns had fused and they had been very badly distorted.

However, the examination of transformer 031 which had failed on 14th December threw a fresh light on the problem. The bulged tank and the evidence of smoke pouring from it suggested that this failure was similar to the others, but when the primary winding was removed there were no signs of burnt insulation on the outer layer of the secondary winding and some oil was still noticeable. The turns of this layer were distorted and were overriding each other badly. A hole was found in the third layer and it extended back to the core, but there was little sign of the turns having moved. The second layer had been badly burnt and some of its turns had fused, as had those of the first layer.

The absence of general overheating and the localised burning of the turns provided evidence for the first time of a failure which was definitely unconnected with the breakdown of the cooling system.

A brief description of the damage to the five transformers is given in Table 15.

Table 15. The five Glasgow transformer failures. Description of damage

Transformer No.	Date	Tank	Primary winding	Secondary winding
003	30th October, 1960.	Bulged, oil sludge reported found.	Good	Paper insulation burnt away or badly charred throughout the layers, many turns fused and others badly distorted. Damage progressively less towards the core: copper bright.
042	14th November, 1960.	Bulged, oil sludge reported found.	Good	Do.
051	13th December, 1960.	Bulged. No sludge found.	Badly shaken, spacers distorted.	Outer layer badly distorted and paper insulation burnt away and charred. Signs of overheating in other layers, getting progressively less towards the core: copper bright.
031	14th December, 1960.	Bulged	Some spacers displaced.	No appearance of overheating. Outer layer badly distorted and turns overriding. Hole in third layer extended back to the core, getting progressively larger. Turns fused over an area of the two layers next to the core.
014	17th December, 1960.	Bulged and cover nearly blown off.	Voltage changeover switch terminal blown out and H.V. leads burnt.	Badly overheated. The paper insulation burnt and charred in the outer layers. Turns seriously distorted, damage getting progressively less towards the core: copper bright.

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113. On 28th December transformer 030 was examined at Wythenshaw as the unit concerned had failed in service when a rise in oil temperature operated the thermostat which tripped the circuit-breaker. The fuse of the oil pump had blown and stopped it from working; consequently it was decided to open the transformer to see whether its condition could throw any light on the main problem.

The two outer layers of the secondary winding showed no signs of overheating but there was serious displacement and overriding of the turns of these layers. Their condition was very similar to that of transformer 031. " Scuffing " of the paper insulation had also occurred on the overriding turns. The turns in the other layers were distorted, but to a lessening degree towards the core.

This transformer was clearly in the early stages of secondary winding failure, and a breakdown of insulation between the overriding turns would probably have followed had the transformer remained in service. Its condition with its distorted secondary winding and overriding turns indicated that it had been subjected to severe electro-magnetic forces which it could not withstand. The lack of any sign of overheating of the windings still further discounted the theory that failure of the oil circulation was the primary cause.

114. Further meetings were held on 1st and 7th January, 1961, at which it was now agreed by all concerned that the transformer secondary windings had been unable to withstand the electro-magnetic forces to which they had been subjected in service. It was stated that the calculations showed that the windings were not strong enough for the short circuits imposed on them.

It was thought that the distortion of the windings was caused by the intense mechanical forces set up probably by rectifier backfires which had occurred very frequently in service. Further contributory factors might have been severe over-voltages due to surges in the overhead line, pantograph " bounce " or the rapid operation of the circuit-breaker. The overheating of the transformer from assisted running or some failure of the cooling system was not entirely discounted.

It was decided at these meetings to rebuild the transformers to a new design, using interleaved coils and to carry out all other necessary modifications. Mr. H. West, the Managing Director of A.E.I., Manchester, announced that the resources of both the A.E.I., Manchester and Rugby Works would be utilised in order to complete the work in the quickest possible time.

115. In the light of the experience gained from the examination of the Glasgow transformers, Mr. Lane inspected all the other types of transformer used in multiple-units. He found that the differences in their design and construction and in their associated equipment was such that there should be no danger of a repetition of the Glasgow failures, but in order to remove all doubt he wished to carry out a further series of tests.

116. During my investigation I decided that it would be desirable to take note of the failures which had occurred on other recently opened high voltage A.C. electrified lines to ascertain whether they and the Glasgow transformer failures were in any way inter-related, and in particular whether the introduction for the first time on any railway of a dual high voltage A.C. system had any bearing on the problem. This further investigation formed the basis of my second interim report completed on 30th May, 1961, and as explained later threw further light on some of the problems associated with the Glasgow failures.

Section IX. Further Investigation and Tests of the Glasgow Equipment

117. After the publication of my first interim report attention was concentrated on getting the modifications made to the multiple-unit trains as quickly as possible and in carrying out comprehensive tests and trials prior to the resumption of public services. At the same time investigations were continued to ascertain the exact causes of the very heavy electro-magnetic forces which had damaged five of the original transformers.

118. Section X describes the modified trains and the tests and trials to which they were subjected. This section covers the further investigations into the original failures and other troubles experienced during trial and service running. The investigations are described under the following heads:

(*a*) Examination of the original transformers.

(*b*) Tests of the original transformers.

(*c*) Examination and tests of paper insulated conductors and transformer oil.

(*d*) Running tests.

(*e*) Review of the troubles experienced with other electrical equipment.

(*f*) Examination of incidents affecting the overhead equipment which might have contributed to the transformer failures.

Examination of the original transformers

119. It was decided to examine all the original transformers at the A.E.I. Works when they were returned for modifications to see whether any of them showed signs of turn movement of the secondary winding. In addition to the five serious failures (*see* Table 15) 19 other transformers were classified as unfit for further service on account of overriding or distorted secondary turns. These included transformer 030 which was examined at Wythenshawe in December, 1960 (*see* paragraph 113).

120. A summary of the condition of all the original transformer windings is given in Table 16.

Table 16. Condition of the original Glasgow transformers

In service	
Failed on account of electrical and/or thermal breakdown of the L.V. windings	5
Unfit for service on account of overriding or displaced turns in the L.V. windings	19
Total unfit for further service	24
Total fit for further service	44
Total in service	68
Never in service	
Subjected to special tests	6
Not used	17
Total manufactured to the original design	91 (*a*)

(*a*) Includes one re-wound for special test.

Tests of the original transformers

Short circuit tests

121. On two occasions during the investigation 25 kV was applied to a transformer with the changeover switch in the 6·25 kV position.

A transformer was undergoing short circuit tests at the Contractor's Works when the changeover switch was left by oversight in the 6·25 kV position. When a 25 kV shot was applied the secondary short circuit current reached a peak of 10,500 amps. On examination the coils of the secondary winding were found to have been distorted and were no longer fit for service.

On the second occasion a test train was deliberately run through a neutral section from a 6·25 kV line to a 25 kV line without permitting the changeover switch to be operated (*see* paragraphs 131 to 133). The circuit impedance was arranged to limit the secondary peak current which reached a maximum of about 5,000 amps, and when the transformer was subsequently inspected the secondary winding was found to be fit for service.

Another transformer withstood Mr. Lane's original short circuit test of nine shots of 0·1 second duration, some symmetrical and some asymmetrical, and one asymmetrical shot of five seconds duration.

122. During a trial run a transformer was subjected accidentally to 50 backfires from an overheated rectifier and its secondary winding was subsequently found to be seriously distorted (*see* paragraph 129).

As the state of this secondary winding before the trial was not known, another transformer that had never been in service was given a short circuit test of 50 symmetrical shots of 0·1 second duration. It withstood this test, but as Mr. Lane considered that some backfires might be asymmetrical, he arranged for a further test with another unused transformer. This was given a short circuit sequence of 50 shots of 0·1 second duration, some symmetrical and some asymmetrical, in a proportion that was agreed with the Contractors.

On this occasion some of the conductors of the primary winding were distorted, blocks were ribbed and dovetail spacers buckled. The conductors of the secondary winding were also badly distorted with overriding turns, and some " scuffing " of insulation. This transformer would have been unfit for further service. It was ascertained later that the test conditions were probably somewhat more severe than those actually experienced on the trial, and this might account for the primary winding being damaged as well as the secondary.

123. Finally, to ascertain the effect of sustained short circuit such as might result from the delayed opening of a circuit-breaker on fault, a transformer was re-wound to the original design and given five shots each of about 10 seconds duration, one symmetrical and four commencing asymmetrical. Turn displacement and " scuffing " of the paper insulation was sufficiently severe to render the transformer unfit for further service.

Over-voltage tests

124. On 22nd December, 1960, a transformer in conjunction with a circuit-breaker was tested at the high power testing station, Trafford Park, Manchester, to ascertain the over-voltages that could be impressed on the windings by a circuit-breaker "chopping" on a 6·25 kV line, and on 3rd January, 1961, a similar test was made on a transformer in a 3-car unit sent specially from Glasgow for this purpose. Some tests were made with an A.E.I. circuit-breaker and some with a Brown Boveri breaker.

During the tests with both circuit-breakers, the highest over-voltages were impressed on the transformer windings when the tertiary winding was loaded and the secondary winding was open circuit. The maxima were of the following order:

Primary winding	.. ..	54 kV i.e. 6 times normal peak.
Secondary winding	.. ..	24 kV i.e. 6 times normal peak.
Tertiary winding	.. ..	2 kV i.e. 5 times normal peak.

The over-voltages from "chopping" with the circuit-breaker on a 25 kV line were much less onerous.

Examination and tests of paper insulated conductors and transformer oil

125. Samples of copper conductor taken from the secondary winding of transformer 003 were found to be still bright under the charred paper. Visual inspection of the other three burnt transformers (Nos. 042, 051 and 014) indicated that the copper turns of the secondary winding were generally bright though they were discoloured in places.

The oil from transformer 051 was chemically in good condition and showed no signs of prolonged overheating. The oil from transformers 003 and 042, when examined directly after their failure, was reported to be dark and thick and to contain sludge.

Overheating tests

126. A series of tests was made to study the effect of overheating of paper covered copper conductors immersed in transformer oil.

Short lengths of conductor and coils of paper-insulated conductor were immersed in transformer oil and subjected to a series of heating tests by passing currents of varying density through them.

These experiments showed that a sustained copper temperature of the order of 230°C. will char paper insulation slowly under oil but not without markedly deteriorating the oil and discolouring the underlying copper. By contrast, temperatures above 260°C. charred the paper insulation very rapidly with little effect on the oil or copper.

Running Tests

Tests in February, 1961

127. Tests were carried out with two 3-car units of the original design during two nights at the end of February, 1961 to investigate voltage surges under normal conditions and to check temperature rise of the main transformer during assisted running.

These units had been fitted with 5-microfarad condensers and 7-ohm resistors across the transformer secondary windings in order to suppress the over-voltages, particularly in the tertiary circuit. The tests proved the efficiency of these suppressors, and no over-voltages were recorded.

128. The assisted running tests lasted for six hours during which time one 3-car unit with four motors in operation hauled a "dead" 3-car unit. Oil temperatures in the radiator of the transformer cooling system were not excessive and were well below the setting of the oil thermostat.

129. On the second night some 50 rectifier backfires occurred in unit 004 during assisted running. They came in a series of five or six in quick succession always during acceleration at maximum, or nearly maximum, secondary voltage. The transformer from this unit was afterwards examined and found unfit for further service (*see* paragraph 122).

130. Current collection was very bad with showers of sparks flying from the pantograph, especially in tunnels and under bridges. This was not surprising as the electric services had been suspended for 2½ months, and the contact wire had been coated with soot from steam trains running in their place. No unusual effects or over-voltages were observed and the condition of the pantographs after the tests was much better than expected.

Tests in May, 1961

131. Further tests were carried out at the end of May, 1961 to see the effect on the transformer windings and to watch the behaviour of the main rectifiers and auxiliary circuits when 25 kV was impressed on the primary windings in parallel, i.e., set for 6·25 kV.

Two 3-car units were used and the voltage changeover switch of one unit was fixed in the 6·25 kV position. The train was run through a neutral section from the 6·25 kV to the 25 kV line with full power on. On passing over the second track magnet which closed the A.B.B. on the 25 kV line, practically all the train lights failed immediately, and the A.B.B. opened.

132. The recording oscillograph showed that a backfire occurred 12 cycles after the breaker closed and lasted for 3 cycles before the circuit-breaker opened. The line current during backfire showed some asymmetry. The over-voltages impressed on the secondary and tertiary circuits before the main rectifiers backfired reach a peak of 14·4 kV in the secondary and 1·5 kV in the tertiary (each four times the normal peak).

During the backfire the current through the secondary reached a peak of 5,000 amps.

In the tertiary circuit the current rose to a peak of 3,500 amps for the first two cycles and then fell to 1,900 amps for the next 10 cycles before the rectifiers backfired; this drop in current was probably on account of the blowing of the tertiary circuit fuses after two cycles of overload and over-voltage.

133. The transformer was examined afterwards and found to be still fit for service. On the other hand, some of the auxiliary equipment was damaged and many of the protective devices had operated. All the four ignition rectifiers and the battery charger rectifiers were damaged. The overload relays had operated and the fuses were blown in the rectifier cooling fan and oil pump circuits as well as most of the fuses in the heating and lighting circuits. None of the roof equipment was damaged.

Review of the troubles experienced with other electrical equipment

The Brown Boveri air-blast circuit-breaker (A.B.B.)

134. The A.B.B. is opened and closed automatically on passing through every neutral section. On the Glasgow suburban lines during service running each A.B.B. averages about 30 automatic break/make operations per day. In addition during the six weeks of service running in November/December, 1960, the opening of the A.B.B. on fault or from pantograph bounce was a very frequent occurrence and consequently the circuit-breakers were subjected to heavy use. Twelve failures were recorded during the period, mainly from post-insulators breaking or from flashovers. As far as can be judged none of them contributed to the transformer failures. This trouble was cured by removing the auxiliary air reservoir which had caused damp air to reach the air blast. It was also found during trial running that on all units the check valves in the air supply system had been wrongly transposed thus causing some restriction in the air flow from the main reservoir.

135. On 25th April, 1961, during tests of a Brown Boveri circuit-breaker, it was noticed that it locked in at higher pressures than those originally specified. This discovery led to an examination of the working of the lock-in device of the Brown Boveri breaker to ascertain whether such an occurrence could have contributed to the transformer failures. It did not apply to the A.E.I. breakers which were not equipped with that device.

136. It will be recalled that each Brown Boveri circuit-breaker originally had been fitted with two safety devices, namely:

(*a*) A governor (A.B.G.) to open the breaker before air pressure had fallen too low for its successful operation, and to keep it open until the pressure rose to a specified figure.

(*b*) A lock-in device to prevent the breaker from opening if the air pressure was too low for its safe operation, and to hold it closed until the pressure had risen sufficiently.

These devices were set to operate at pressures well below those which operated the main air compressor governor. The original settings are given in Table 17.

Table 17. The Brown Boveri air-blast circuit-breaker. Original setting of safety devices to control air pressure and breaker operation

Device	On falling air pressure		On rising air pressure	
	Action taken	Pressure p.s.i.	Action taken	Pressure p.s.i.
Main air compressor governor ..	Compressor started ..	85	Compressor stopped ..	100
A.B.G.	A.B.B. opened	59	A.B.B. re-closed ..	75
Lock-in device	A.B.B. locked-in (nominal setting).	52	A.B.B. opened (nominal setting).	60

137. Investigations into the operation of the Brown Boveri breaker showed that the lock-in device, which was not intended to be a precision instrument, could vary in its setting between one breaker and another and also from day-to-day in an individual device, depending on the friction in the operating mechanism. The tests proved that in an extreme case the device could lock-in at a pressure as high as 65 p.s.i.

138. As a result of these tests and after due consideration of the value of the lock-in device, it was decided to remove it from all Brown Boveri circuit-breakers and to rely on the A.B.G. for protection against failure from low air pressure. This bas now been done but before their removal all the lock-in pressures were checked. Although 64 per cent. of the devices locked-in at pressures between 50 and 54 p.s.i., two locked-in at 60 p.s.i. and three at pressures as low as 45 p.s.i. This examination confirmed that the setting could vary between wide limits. The pressures at which the A.B.G. operated were checked and found to be more reliable.

139. These investigations have shown that danger from a circuit-breaker locking-in irregularly could arise when the following conditions were satisfied:

(*a*) There was a leak in the compressed air system or a drop in pressure from other causes which could not be overcome sufficiently rapidly by the air compressor.

(*b*) The setting of tbe lock-in device on falling pressure was higher than the setting of the circuit-breaker governor (A.B.G.).

(*c*) The lock-in device operated and so prevented the A.B.B. from opening at the moment when a fault occurred in the power equipment or when the unit was passing from a 6·25 kV to a 25 kV section.

Should the first two conditions be satisfied, the circuit-breaker could lock-in and would not then open until the air pressure rose sufficiently for the lock-in device to free itself and allow the breaker to operate normally.

140. The chance of all of the above conditions being satisfied simultaneously is slight, but it cannot be ruled out entirely and it is possible that one or more of the transformer secondary windings might have been damaged by a lock-in of this type. Twelve of the incidents at neutral sections which have been associated with tbe mal-operation of the A.P.C. might alternatively have been due to a breaker sticking in (*see* paragraph 148). No authenticated case of an A.B.B. having failed to open has been establisbed, thougb several instances of an A.B.B. failing to close have been recorded.

The Automatic Power Control (A.P.C.) equipment

141. During trial and service running the A.P.C. operated irregularly on a number of occasions thereby turning tbe changeover switch on the transformer to the 6·25 kV position wben the train was on the 25 kV section of the line. As mentioned in paragrapbs 131 and 132, a test showed that such an operation could cause the rectifiers to backfire.

A number of these incidents were associated with overhead line faults (*see* paragraphs 154 to 158), to which the A.P.C. was particularly sensitive in tbe early days of operation. To appreciate how these arose it is desirable to amplify the general description of the equipment as given in paragraph 65.

The line voltage detection circuits

142. The A.P.C., as developed by A.E.I., Manchester to meet the Britisb Railway's specification, is based on the voltage sensitivity of four transductors which respond only to specified ranges of line voltage and control the operation of four voltage relays. Of these, V.R.1 alone closes the circuit for the 6·25 kV settings, but the other three—V.R.2A, V.R.2B and V.R.3—in addition to V.R.1 must close before tbe switch can throw to the 25 kV position.

The accepted variations in overhead line voltage are:

6·25 kV line	4·1 kV to 6·9 kV
25 kV line	16·5 kV to 27·5 kV

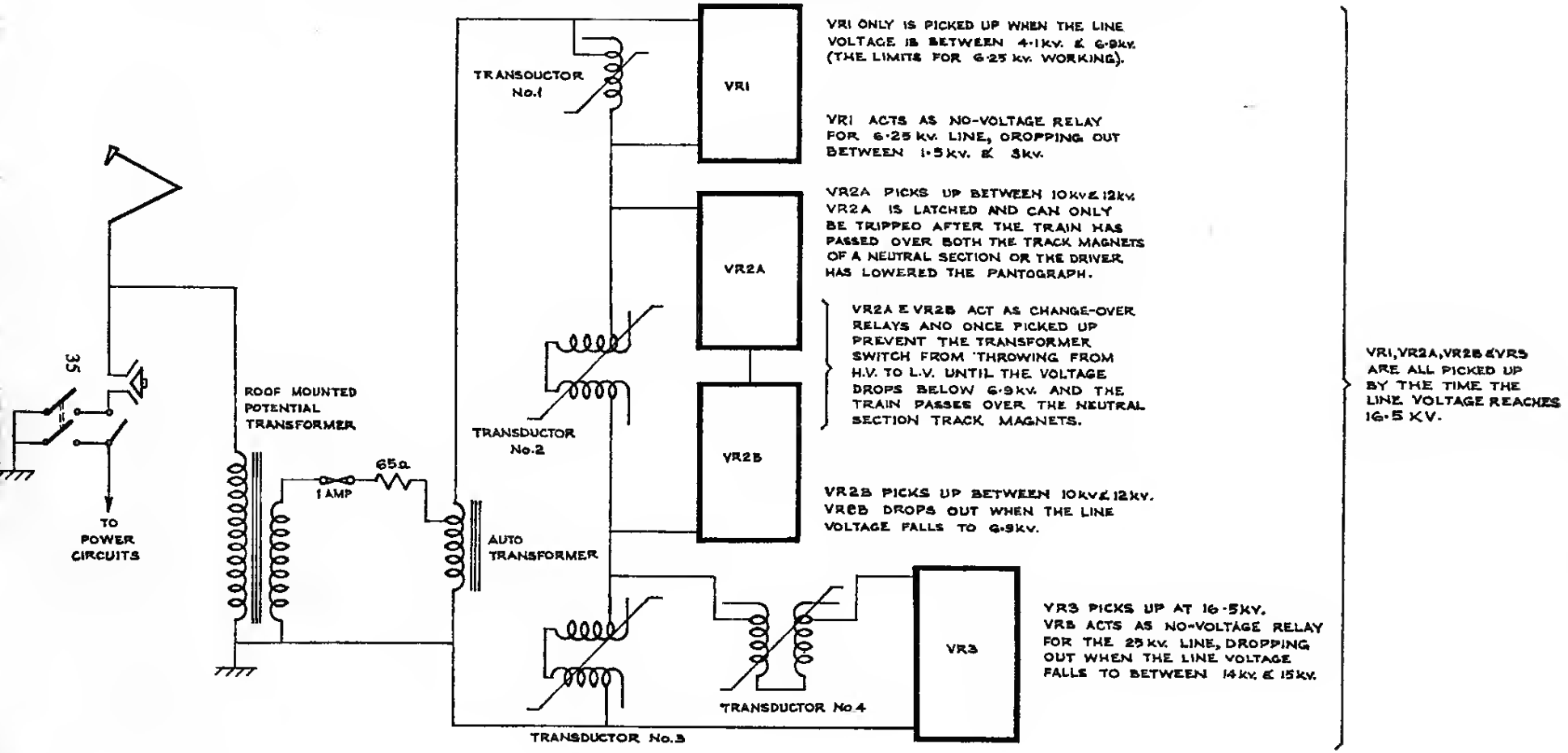
The transductors have been designed to respond to these variations but the operations of the relays were twice altered as a result of experience gained in trial and service running. These two modifications as well as the original design are briefly described in the following paragrapbs, and a simplified diagram of the relay operations after modification is sbown by Fig. 2.

Original design

143. On the 6·25 kV line. Relay V.R.1 alone picked up when the line voltage rose to 4·1 kV and thereby allowed tbe control current to pass to a magnet valve in the cbangeover mechanism whicb turned the switch to the 6·25 kV position, provided the A.B.B. circuit was open. As soon as the switch was in position a contact on the A.B.B. circuit was closed thus enabling the breaker to re-close and restore power to the train.

Fig. 2. Automatic Power Control

simplified diagram of relay operations after modification (as developed by A.E.I. Manchester)



144. On the 25 kV line. All four relays picked up progressively until the voltage reached 16·5 kV when the last connection through V.R.3 was made and the current passed through another magnet valve in the changeover mechanism and threw the switch into the 25 kV position, provided again that the A.B.B. circuit was open. This was achieved when the equipment passed over the first track magnet of a neutral section thus causing all relays to drop out before they picked up again. V.R.3 acted as a no voltage relay, dropping out and opening the circuit-breaker when the line voltage fell below 14 kV.

Relays V.R.2A and V.R.2B acted as changeover relays, and once they had picked up they prevented the changeover switch from throwing from the H.V. to the L.V. position until the line voltage had dropped below 6·9 kV. With this scheme, on falling voltage, the line voltage had only to drop below 6·9 kV for about $\frac{1}{2}$ second for the changeover switch to operate. If this occurred as a result of a temporary fault on the 25 kV line the changeover switch would be in the L.V. position when line voltage was restored to normal and thus allow 25 kV to be impressed on the 6·25 kV windings.

First modification

145. Owing to the sensitivity of the A.P.C. equipment to induced voltages and the effect of voltage " gradients " in the overhead line, the first modification was made on 6th October, 1960. A mechanical latch was fitted to relay V.R.2A which could only be unlatched by relay V.R.1 tripping out when the line voltage fell below 3 kV; thus the changeover from H.V. to L.V. could only take place after the line voltage had dropped below this level and then had risen again to at least 4·1 kV.

The second modification

146. The first modification did not fully overcome the effect on the A.P.C. equipment of variations in line voltage; in fact over half the suspected incidents occurred after the modification had been made. Consequently a second scheme was devised and executed when the other major alterations were made after the units were withdrawn from service.

Under the new scheme the latch on relay V.R.2A can now only be tripped after the equipment has passed over both the track magnets of a neutral section or the motorman has lowered the pantograph. In addition a delay of between one and two seconds has been applied to the closure of the circuit-breaker after the receiver has passed over the second track magnet, or the pantograph, after having been lowered and reset, reaches the overhead live wire again.

Wrong changeover during trial and service running

147. It will be seen from the above descriptions that the A.P.C., as originally designed, was sensitive to variations in the line voltage, and the changeover switch could be thrown to the 6·25 kV position by a drop in voltage from a line fault whilst the train was running on the 25 kV section; then it only required the clearance of the fault to impress 25 kV on the 6·25 kV winding before the A.B.B. had time to open and thus allow the A.P.C. to throw the changeover switch back to the correct position.

The history sheets of all units in service have been examined to trace incidents of damage which might have been caused by wrong voltage changeover and to associate these where possible with the faults in the overhead line equipment. Attention was concentrated primarily on blown fuses and other damage to equipment in the tertiary circuit because it was considered that the over-voltages and currents generated by wrong changeover would be so high in that circuit that some sort of damage would undoubtedly be evident. On the other hand, the over-voltages in the secondary circuit would not necessarily cause damage unless associated with simultaneous rectifier backfires.

148. Mr. Lane has recorded 38 incidents when blown fuses and other damage to equipment in the tertiary circuit suggested that over-voltages in that circuit were the result of wrong changeover. There may have been other changeovers which did not blow fuses or cause any noticeable damage, but this cannot be checked.

On 4th May, 1960, the omission of a line jumper at Dalmuir Park caused one suspected changeover and possibly another. On 15th June two incidents were associated with line faults at Dalreoch, and on 28th June six incidents were associated with similar faults at Drumchapel. During November seven suspected incidents may have resulted from mal-operation when passing through the Parkhead neutral section, and five more when passing through the Westerton neutral section; alternatively some of these 12 incidents might have been the result of a circuit-breaker sticking in (*see* paragraph 140).

The other six incidents could not be associated with any recorded line faults and they may have been the result of high over-voltages caused by the circuit-breaker " chopping " on the 6·25 kV line.

149. The 38 incidents affected 29 transformers; of these No. 003 was subjected to suspected wrong changeover on 18th May, 1960, and finally failed on 30th October, 1960 (*see* paragraph 103). All the other 28 transformers continued in service but when they were examined prior to modification, nine were found to be unfit for further service on account of overriding or displaced turns in the secondary winding.

Mr. Lane's investigations showed that only on five occasions was there any record of secondary circuit overload relay operation on the same days as the 38 suspected voltage changeovers, and of the five transformers affected only two were afterwards found unfit.

The rectifiers

150. During trial running some trouble was experienced from backfiring rectifiers and a number with suspected defects were returned to the Contractor's Works, but during the whole period of trial and service running only 13 out of 272 in service had to be repaired on account of defects; the others were modified to incorporate improvements made as a result of the trials.

The ventilating shutter mechanism gave some trouble during the last fortnight of trial running but this was practically cured by giving more attention to maintenance. Backfires continued, however, at a high rate.

The exact number of rectifier backfires could not be recorded because the motormen were not in a position to verify such irregularities. Normally, however, a backfire imposes a short circuit on the secondary winding of such magnitude as to operate the overload relays and trip the A.B.B. The frequent tripping of the A.B.B. was a most significant feature, and it became so frequent that resetting was often accepted as part of the day's routine and was not reported. There is little doubt that the actual number of backfires far exceeded the reported number of overload operations during the six weeks of service running in November/December 1960.

151. The rectifier shutter mechanism was redesigned before the modified units began trial running in March, 1961. This made it more positive in action, and better thermostats improved its control, but rectifier backfires have continued until recently at an undesirably high rate. Detailed and continuous investigations have been made into the working of the rectifier in service and many laboratory tests have been carried out. The cause has now been traced to unfavourable anode/cathode temperature differential, and a modification has been made to remedy this.

Traction Motors

152. The traction motors have performed excellently and no failures of any significance have been recorded during trial and service running. This is a remarkably fine achievement, especially in view of the bad conditions of service under which the units operated, including severe over-voltages from A.B.B. "chopping" on the 6·25 kV lines and irregular voltage changeover on the 25 kV lines; in addition assisted running for long periods caused some overheating.

Faults in the tertiary circuit

153. The faults in the tertiary circuit were mainly blown fuses, failures of the oil pump proving relay rectifiers and failures of the battery chargers, all largely attributed to severe transient over-voltages when operating on the 6·25 kV lines.

Examination of incidents affecting the overhead equipment which might have contributed to the transformer failures

154. This review only covers those types of incident which might have affected the operation of the A.P.C. on the motor units. They were all concerned with variations in line voltage from one cause or another and with movements through the neutral sections.

The variations in line voltage might have occurred as a result of:

(*a*) Induced voltages in a "dead" line.

(*b*) Voltage gradients during fault conditions.

(*c*) Incidents at neutral sections.

Induced voltages

155. It was found that with one line "live" at 25 kV and an adjacent line "dead", voltages up to 5 kV could be induced into the "dead" line. The omission of an overhead jumper in the Dalmuir Loop during early days of trial running (4th May, 1960) left a short section of line nominally "dead", but actually with sufficient induced voltage to cause irregular voltage changeover on two units that passed through the loop on to the 25 kV line. The transformer of one of these units was found with overriding turns when it was examined after the services were withdrawn. On the other hand, the second unit's transformer was found in good condition.

Voltage gradients

156. The opening on fault of a feeder circuit-breaker at one end of a section before the other operates, produces a voltage gradient dropping from the feeding end to zero at the fault. As already described in paragraph 27, the line protection arrangements are such that the great majority of faults cause the second breaker to open within one second of the first. Should such a fault occur on a 25 kV line, the

drop in system voltage may have heen sufficient to cause trains on this or an adjacent section to change over to the 6·25 kV position. On the adjacent section 25 kV would be momentarily imposed as soon as the line breaker cleared the fault, whilst on the faulty section the transformer would have 25 kV imposed on it the moment a line breaker was reclosed.

157. The most notable incidents occurred on 28th June, 1960 when mischievous boys threw wires over the 25 kV lines near Drumchapel on two occasions. The short circuits opened the line hreakers at Westerton and Dalmuir Park and, as a consequence, six units in the vicinity may well have suffered wrong voltage changeover. Although this caused considerahle damage to fuses, rectifiers etc. in the tertiary circuits, none of the secondary overload relays operated. In the final examination of the transformers five were found in good condition and one with some secondary turn displacement sufficient to render it unfit for further service.

It is satisfactory to record that the hoys were caught and punished.

Incidents at neutral sections

158. The chief trouhle occurred at the Parkhead neutral section. It was found that the exit magnet on the Up line was too close to the neutral section and at the same time a " ghost " voltage of 4 kV was appearing in the overlap span of the neutral section nearest to the 25 kV " live " line. The " ghost " voltage caused the A.P.C. to throw the changeover switch to the 6·25 kV connection immediately hefore entering the live 25 kV line, and when trains travelled through the section too fast, the A.P.C. had insufficient time in which to respond to the 25 kV " live " line before the magnet closed the A.B.B. and impressed that voltage on the 6·25 kV connections.

The " ghost " voltage was removed on 20th November, 1960, by fitting a capacitor between the neutral section nearest to the 25 kV line and earth. The magnet had been moved further out a few days earlier to give more time for the operation of the A.P.C. equipment.

Section X. The Modified Glasgow Trains, Their Trials and Performance

The modification plan

159. As I have already mentioned, urgent plans were made for the re-winding of all the transformers and for carrying out all the other modifications found necessary as a result of the experience gained during trial and service running.

The full resources of the Manchester and Rugby Works of A.E.I. were used for the re-winding of the transformers and for carrying out the other electrical modifications. The Pressed Steel Company who had built the original units at their Glasgow Works co-operated wholeheartedly and undertook the consequential alterations to the mechanical equipment. The London Midland Region placed their Dukinfield Railway Works near Manchester at the disposal of the Scottish Region, and all major modifications were made there.

Progress of the work

160. Altogether 77 motor coaches were re-equipped at Dukinfield in five months—a very fine joint achievement by the staffs of the two Contractors and of the London Midland and the Scottish Regions.

The remainder of the fleet, namely 14 sets, were completed at the Pressed Steel Company's Works. These were the units needed to supplement Phase II of the Glasgow electrification which has not yet been hrought into use.

The first modified design of transformer was type-tested satisfactorily on 22nd February, 1961, and the first reconstructed train comprising two 3-car units was suhjected to oscillographic and other tests during the nights of 21st, 22nd and 23rd March.

The main modifications

The transformer

161. The main transformer windings have heen redesigned. They are now made up of a series of " pancake " coils of primary and secondary windings interleaved in suitably disposed groups with the tertiary winding at either end. The turns in each coil of the secondary winding are of stronger construction than those in the original windings and the strength of the redesigned transformer to resist electromagnetic forces is now very much greater than the strength of the original transformer. This was demonstrated when the new transformer was given a severe short circuit test of 50 shots each of 0·1 second; 20 at 1·5, 15 at 1·3 and 15 at 1·0 asymmetry; it also had 25 kV impressed on the 6·25 kV winding with the secondary short-circuited. Afterwards the transformer was found to he in perfect condition with no signs of damage or distortion of any kind, in contrast to the damaging effect of the same test on the primary and secondary windings of a transformer of the old design.

Transformer protection

162. The oil circulating system has also heen modified. The system now works under positive pressure. A 1¼-in. diameter pipe in place of a ½-in. diameter pipe connects the transformer tank with the conservator which is now mounted on the outside of the coach. The vent to atmosphere is now through a 2-in. diameter pipe with an oil seal; it is quite independent of the silica-gel breather. A Buchholz relay has heen fitted directly above the transformer tank in the outlet pipe so as to detect immediately the formation of gas or undue turbulence in the oil circulating system. The operation of this relay opens the circuit-breaker and it cannot then be re-set by the motorman. An oil pressure switch has heen provided to replace the oil pump proving relay and it also opens the A.B.B. in the event of interruption in the oil circulating system.

Finally, a primary overload relay has heen fitted in addition to the existing primary differential relay. This will ensure that the circuit-breaker will he opened whenever the current through the primary circuit exceeds a predetermined amount, such as might result from some kinds of inter-turn short-circuiting.

Other modifications

163. Many other modifications were made prior to the resumption of trial running. They included the following:

(i) *Air-blast circuit-breaker*

The Brown Boveri air-hlast circuit-hreaker was modified hy the removal of the lock-in device, as explained in paragraph 138, and improvements have heen made to the air supply arrangements.

(ii) *Automatic power control*

The voltage selection arrangements were redesigned and the timings of the various relays altered so as to eliminate as far as practicahle incorrect changeover. Details of the changes are given in paragraphs 145 and 146.

(iii) *Secondary circuits*

A 5-microfarad capacitor in series with a 7-ohm resistor was fitted across the secondary winding terminals to reduce the transient over-voltages through the secondary and particularly the tertiary circuits.

(iv) *Rectifiers*

The ventilating shutters were modified and more positive mechanism was provided. Better thermostats were fitted.

(v) *Battery charger*

The battery charger was modified to give greater resistance to voltage surges.

(vi) *A.B.B. indicator*

An indicator lamp which lights whenever an A.B.B. trips was fitted in the motorman's cab.

The initial tests

164. Modified Units 064 and 058 were used for the initial tests, the former being equipped with measuring instruments. The tests which were carried out on the nights of 21st, 22nd and 23rd March, 1961, included:

(*a*) Voltage surge investigations.
(*b*) The operation of the A.P.C. equipment.
(*c*) Acceleration tests.
(*d*) Assisted running tests.
(*e*) Heating tests of—
  (i) Transformers
  (ii) Rectifiers
  (iii) Traction motors.
(*f*) Protection against hackfires.

165. No signs of surges were noticeahle in the secondary circuits and it seems that the surge suppressors have effectively suhdued the over-voltages, though some surges were still noticeahle in the tertiary circuits.

166. The A.P.C. equipment operated satisfactorily. The rectifiers gave no trouhle and no backfires were recorded. Under assisted running conditions the transformer and traction motor temperatures were not excessive, but it was decided to limit the period of running to a maximum of 40 minutes at a time.

167. It was agreed that these tests were so satisfactory that the modified multiple-unit trains could begin running on a definite scbedule on 27th March, 1961.

Trial running

168. Regular trial running began on 27th Marcb, 1961. The total mileage up to the re-opening of public services on 1st October was 380,000 miles. As a result of this testing some further minor modifications were made before public services were resumed.

Final tests and examinations

169. Prior to carrying out full scale tests with the modified trains I visited Glasgow on 13th and 14th September, 1961, and reviewed with Mr. Lane and the officers of the Commission, the Scottish Region and A.E.I. the performance of these trains during trial running. I also tested all the safety equipment and studied the working of a modified train under various conditions of operation, including hauling a 6-car train with two motors only, four motors only and with full power. During this test I watched tbe operation of the automatic power control equipment and the working of the circuit-breaker. I also made comprehensive brake tests and generally observed the performance of the train under all conditions. As a result of these tests and my discussions with the officers concerned, I felt satisfied that the modified trains would give satisfactory service and I could see no objection to public services being resumed, subject to satisfactory performance during the two trials mentioned below.

170. On Sunday, 17tb September a full-scale trial with service running on the standard electric timings was carried out. Unfortunately, owing to the phenomenal storm on the previous day, only two-thirds of the number of trains could be run because seaweed and other debris from the storm was not cleared until 11.0 a.m. The trial indicated that there was little wrong with the equipment, but it was decided to make a further trial on Sunday, 24th September. This was highly successful and a full train service was run, virtually without a hitch. As a result the British Transport Commission decided that the public service could be resumed on Sunday, 1st October.

The results achieved in service running

171. The Scottish Region restored the Glasgow electric services on Sunday, October 1st, 1961, and a full service has since operated with marked success. The " Blue " trains—as they are familiarly known in Scotland—bave already established in the public mind an excellent reputation for punctual and reliable service. Out of some 8,300 booked trains which ran during the first four weeks of service, more than 92 per cent. arrived at destination on time. Since then they have continued to give excellent service and by 31st December, 1961, they had already run for over one million miles.

During this period a number of minor troubles were experienced incidental to starting a major suburban electric service. Rectifier backfires continued at an undesirably high rate until recently, but the trouble has now been cured as explained in paragraph 151. The modified transformers have withstood the electro-magnetic forces produced by these backfires and recent examination bas shown that they are in perfect condition to give continued reliable service.

During the first three months of the resumed service tbe train failure rate from electrical faults bas averaged one in 70,000 miles. The faults were all of a minor character and none was fundamental

Section XI. Conclusion and Remarks on the Glasgow Failures

Introductory

172. These conclusions and remarks are based on examinations of equipment, on numerous reports on its performance, on tests of all types, and on meetings with the Commission's officers and the Contractors, but above all on the detailed and exhaustive investigations carried out by Mr. F. J. Lane and his staff.

A summary of the initial investigations is given in Section VIII and a description of the further investigations and tests in Section IX.

The transformer

Preliminary remarks

173. It will be noted from Table 16 that in addition to the five transformer failures described in Section VII a further 19 transformers were found on examination to be unfit for further service; thus out of a total of 68 that were in action during November/December, 1960, 24 transformers or 35 per cent. were damaged or found damaged afterwards.

174. The transformers had, however, been well built of first class materials and they were well balanced electrically. One of them withstood Mr. Lane's original test of 10 short circuits of varying intensity—a test which up till then had been considered more severe than any that need be applied to a traction transformer. The secondary winding of another was only slightly affected by 50 symmetrical shots although the winding was seriously overheated in the process, whilst a third was virtually undamaged after a backfire resulting from 25 kV being impressed on the 6·25 kV winding.

175. The running of experimental equipment on the Lancaster–Morecambe–Heysham line and the early trials on the Styal and Glasgow suburban lines gave no indication of troubles to come. The investigations and tests described in Section IX have demonstrated the strength of the transformer, but they have also shown that the secondary windings were not strong enough to withstand the frequent application of severe short circuits to which they were subjected in service.

176. The secondary winding comprised five layers of copper conductor wound one on top of the other leaving the outer layer less supported than the others and dependent largely for its stability on the tension applied to the turns. This was effective to meet normal conditions, but, when heavy electro-magnetic forces were applied some turn movement could take place and cause slight loosening which became progressively worse with each successive application of force. Similarly, excessive heat could expand the copper and might also cause turn loosening. Slight variations in the turn tensioning during manufacture might account for some transformers suffering more damage than others.

The damaged transformers

177. The damaged transformers can be classified under two heads:

(*a*) The five that failed in service as described in Section VII.

(*b*) The nineteen other transformers with overriding or displaced turns in the outer layers of the secondary windings sufficiently serious to render them unfit for service.

Causes of Breakdown

178. The running records of all the units while on trial and in service were examined and this evidence showed that the transformers were subjected to exceptionally severe treatment from short circuits caused by backfires.

The static and running tests suggested that the transformer would withstand a limited number of short circuits but that it might fail if subjected to a long succession of such incidents, or to a number of sustained short circuits, or to a short circuit associated with excessive over-voltage.

179. There was evidence to show that the Brown Boveri circuit-breaker could lock-in, but no direct confirmation that it did so in service. There was also evidence that the mal-operation of the A.P.C. caused 25 kV to be impressed on the 6·25 kV primary windings of some transformers, and that severe over-voltages were produced by the circuit-breaker " chopping " on the 6·25 kV lines.

180. Other tests indicated that high currents passed through coper coils immersed in transformer oil would heat them very rapidly and char the paper insulation with little effect on the oil or copper. On the other hand, sludge had been found in the first two of the failed transformers which suggested that they had been subjected to long periods of overheating during some period of their service.

181. The secondary winding of four of the five failed transformers were very badly burnt with severe distortion and fusing of the turns of the outer layers; this damage got progressively less towards the core.

182. The evidence quoted above is to some extent conflicting and confusing and it is not possible to pin-point one exclusive cause of transformer breakdown. It seems, however, that the damage was caused principally by the frequent application of severe electro-magnetic forces, sufficient gradually to distort the outer layers of the secondary windings. This led to the over-riding of turns, high inter-turn pressure, the scuffing of the paper insulation, and its eventual breakdown.

183. Four of the five transformers that failed appear to have reached the condition in which the paper insulation had become so damaged that it finally broke down and allowed inter-turn short circuits to be set up. Severe internal heating caused by the high current flow would follow almost immediately. The heat and arcing so generated would have been sufficient to gasify the oil rapidly and distort the windings before power was cut off. It will be appreciated that these transformers were protected by primary differential relays which in some circumstances would be slow to operate.

The nineteen damaged transformers had also been subjected to similar severe treatment to a greater or lesser degree, and had the service been continued with rectifiers still prone to backfire they might well have failed in a similar way.

Overheating of the first two failed transformers may have been a contributory factor by affecting the mechanical strength of the paper insulation and/or loosening the conductors in the outer layers of the secondary windings.

184. The failure of the other transformer (031) was of a somewhat different character. It seems to have resulted from a severe over-voltage surge which broke down the paper insulation on an inner turn and so caused the internal short circuit that fused the turns and damaged the inner layers of the windings.

Conclusion

185. All these facts suggest that although the transformers were capable of withstanding a measure of abnormal treatment, some of them could not stand up to the very arduous conditions of service to which they were subjected.

I have little doubt that the primary causes of these failures were frequent short circuits resulting from the backfiring of the rectifiers. The irregular locking-in of the circuit-breaker during backfire and high over-voltages associated with backfires may have been contributory factors in a few cases, and overheating may have caused some damage in two cases, though it was not in itself a primary cause. One transformer seems to have failed finally from a severe voltage surge.

Rectifiers

186. Most of the rectifier backfires which were a constant source of trouble were caused by overheating or unfavourable anode/cathode temperature differential. It is thought that the latter was probably the main cause because backfires, which continued at a high rate after the ventilating arrangements were made fully effective, have virtually ceased since the heat differential has been modified.

Traction motors

187. The traction motors have performed excellently and no failures of any significance have been recorded during trial and service running. This is a fine achievement.

Over-voltages

188. The equipment was at times subjected to severe transient over-voltages. The most constant source was from both types of air-blast circuit-breaker " chopping " on the 6·25 kV lines. This produced maxima through the various windings up to six times the normal peak. These were comparable to those experienced with the North-East London units but their effect was not so serious on account of the additional protection applied to the Glasgow units and the difference in the circuits.

189. Another possible source of over-voltage was from the Brown Boveri air-blast circuit-breaker locking-in. This breaker was originally equipped with a lock-in device which was not intended to be a precision instrument and could vary in its setting within wide limits depending on the friction in the operating mechanism. It was found that at times this device might operate at a higher pressure than that of the lock-out governor which should normally open the breaker before air pressure falls too low.

Should the circuit-breaker be locked-in when passing through a 6·25/25 kV voltage changeover neutral section, severe over-voltages would be impressed on the transformer secondary winding and any consequential short-circuit current would be sustained until the breaker unlocked. As explained in paragraph 140, the chance of danger arising from such a cause was slight but it could not be ruled out entirely.

190. During trial and service running the automatic power control (A.P.C.) equipment operated irregularly thereby turning the changeover switch on the transformer to the 6·25 kV position when the pantograph was on the 25 kV line. Such mal-operation caused severe over-voltages, but there is little positive evidence that they damaged the transformer secondary windings, though such over-voltages would have been contributory factors had backfires occurred at the same time.

Auxiliary equipment

191. Over-voltages from the causes mentioned above may have contributed to the transformer failures but there is no doubt that they caused damage to the equipment in the tertiary circuits. Voltages of the order of 2 kV were impressed on this circuit from the A.B.B. " chopping " on the 6·25 kV lines and voltages of 1·3 kV arose from impressing 25 kV on the 6·25 kV winding of the primary. In addition to blowing fuses these heavy voltage surges damaged the auxiliary excitation and ignition rectifiers, the oil pump proving relay rectifiers and the battery chargers.

Summary of modifications

192. Steps have been taken to eliminate as far as practicable all sources of trouble, and the modifications include the following:

(*a*) The transformer windings have been redesigned and are now of the " pancake " coil type, and their resistance to electro-magnetic forces is very much greater than before.

(*b*) The transformer oil circulating system has been modified and the conservator tank is now mounted outside the coach.

(*c*) Additional transformer protective devices have been provided including a primary overload relay, a Buchholz relay and an oil pressure switch.

(*d*) Additional surge suppressors have been fitted across the secondary winding to reduce voltage surges in both the secondary and tertiary circuits.

(*e*) The automatic power control system has been so modified as virtually to eliminate the chance of wrong changeover.

(*f*) The lock-in device of the Brown Boveri air-blast circuit-breaker has been removed, and modifications have been made to the air circuits.

(*g*) The ventilating shutters of the rectifiers have been made more positive in operation, better thermostats have been fitted, and the anode/cathode temperature differential has recently been modified.

(*h*) The battery charger has been modified to cope with higher over-voltages.

(*i*) An A.B.B. indicator lamp has been fitted in each motorman's cab.

Concluding Remarks

193. The results achieved since the modified units have been running on public service have demonstrated the efficacy of these improvements and I am satisfied that the Glasgow multiple-units will give safe, reliable and efficient service now and in the future.

PART IV. THE FAILURES OF THE MULTIPLE-UNIT TRAINS RUNNING ON THE NORTH-EAST LONDON (EASTERN REGION) ELECTRIFIED LINES

Introductory Remarks

194. On 30th May, 1961, I presented my second interim report in which I described the troubles experienced with the North-East London multiple-units fitted with G.E.C. electrical equipment and the action taken to correct the faults. I pointed out that the failures of the traction motors and auxiliary equipment resulted primarily from transient over-voltages of high magnitude. I explained that the cause of the mercury arc rectifier failures was more complex and had not been completely established though the Contractors were confident that their proposed modifications would be effective. I drew attention to certain transformer defects which arose shortly before my interim report was completed.

195. The work of applying the agreed modifications was by no means an easy task, as it involved altering the circuits of 71 traction motor equipments and 71 transformers, and the reconstruction of 600 mercury arc rectifiers, as well as the provision of other additional safeguards.

196. This part of my final report contains a summary of my interim report, a description of the work that has been done since then and of the action taken by the Commission regarding the re-winding of the transformers and the changeover of the rectifiers. It is based on reports from the Commission and the Contractors, on inspection of equipment, and in particular on the advice that I have received from the Consulting Engineers, Mr. E. L. E. Wheatcroft, Mr. T. W. Wilcox and Mr. F. J. Lane. It is divided into the following Sections:

Section XII. Review of the troubles experienced with the North-East London units.

Section XIII. Technical investigations and actions taken to correct the faults in the North-East London units.

Section XIV. Conclusions and Remarks on the failures of the North-East London multiple-unit trains.

Section XII. Review of the Troubles Experienced with the North-East London Units

Trial running

197. As already explained, trial running of a prototype North-East London unit began on the Colchester–Clacton line in October, 1959. The unit ran altogether for 25,500 miles until it was withdrawn in July, 1960, for the replacement of the prototype equipments by production types. It did not develop any serious faults.

As further North-East London units were completed they were taken to the same line for commissioning, trial running, and the training of motormen. All the 71 units of the fleet were tested for varying periods between 13th April and 28th December, 1960. There were some failures of rectifier cylinders and two battery chargers had to be changed.

198. In May, 1960, further trial running began on the Rye House–Hertford East section of the North-East London suburban system which was energised at 25 kV. Trial running was extended as further sections of the overhead equipment were energised, but it was not until 30th September, 1960, that the first 6·25 kV section was ready. Thus most of the trial running was carried out on the 25 kV lines. During this period more rectifiers and a few battery chargers failed. The tripping of overload relays was a fairly common feature and the blowing of the tertiary fuses, which was becoming a regular occurrence, led to the examination of the transformers and the strengthening of their tertiary winding connections, as described in paragraph 207.

There were no motor failures, and the troubles up to that time were still considered to be of a transitory character.

Service running

199. On 14th November after the successful completion of the changeover of the Liverpool Street–Shenfield–Southend (Victoria) electrification from 1,500 volts D.C. to 6·25 kV A.C., a public service on steam timings was introduced on the North-East London lines, and this continued for a week.

During this week when 40 North-East London units were in operation, some more rectifier cylinders failed, but this was attributed to deterioration of vacuum while the train sets were stabled for long periods at a time during trial running. There were no transformer or motor failures and accordingly it was decided to proceed with the public services as planned.

200. The full services began on 21st November with a peak traffic of 18 trains per hour and an off peak of 14 trains per hour in and out of Liverpool Street; most of these trains ran on the Chingford and Enfield lines, energised at 6·25 kV only.

Unfortunately the services were seriously disrupted on the first and following days by failures of various types of which the most serious were the breakdown of numerous traction motors and battery chargers, though a few rectifiers also gave trouble. Eventually on 12th December the service was reduced, though sufficient trains were run to cope with the traffic without serious inconvenience to passengers. These results were achieved largely by using stock destined for the London, Tilbury and Southend line.

201. On 14th December the first series of modifications, known as the "A" modifications, was agreed and the work was put in hand forthwith. It took some time to complete and was only partially successful. During the next month more motors failed as well as a number of rectifier cylinders.

202. An important meeting was held on 8th January at the Contractor's Works and another series of modifications, known as the " B " modifications, was agreed. Plans were also made for the equipping and running of a mobile laboratory in a test train; a description of this train and the results achieved by it are given in the Appendix.

During the next four months failures of traction motors and rectifiers were the chief causes of the trouble; battery chargers on the other hand gave better service. On 28th April a transformer failed, as described in paragraph 209.

203. All the " B " modifications were completed by 16th March, 1961, and others, known as the " C " modifications, were put in hand based on information obtained from the running of the test train. There have been more traction motor failures from time to time but these are considered to be the aftermath of damage initiated by over-voltages in the early days before the " B " modifications were made.

The cause of the rectifier failures was most difficult to trace, but as a result of meticulous laboratory examination and analysis the Contractors decided to make further modifications; these formed part of the " C " modifications and are described in paragraph 213.

204. Since 3rd May, 1961, the chief cause of trouble has been the rectifier. The " C " modifications were only partially successful and further tests and trials were carried out. Further modifications have been made and the rectifiers now appear to be functioning far better than before, but they require excessive maintenance to keep them in good order.

205. A summary of the failures and failure rate per thousand unit miles of the North-East London units during trial and service running up to 31st October, 1961, is given in Table 18.

Table 18. Failures of North-East London units during trial and service running

	Trial running			Service running North-East London and Colchester–Clacton lines						
	Colchester–Clacton lines		North-East London lines	Steam timing	Full electric service	Reduced electric service				
	Prototype	Commissioning								
1. Period	28th Oct., 1959, to 14th July, 1960	13th Apr. to 28th Dec., 1960	23rd May to 13th Nov., 1960	14th–20th Nov., 1960	21st Nov. to 11th Dec., 1960	12th Dec., 1960, to 7th Jan., 1961	8th Jan. to 16th Mar., 1961	17th Mar. to 3rd May, 1961	4th May to 31st July, 1961	1st Aug. to 31st Oct., 1961
2. Unit miles run	25,500	35,800	50,400	36,500	177,000	128,000	290,000	387,000	480,000	509,000
3. Failures:										
(*a*) Motors	0	0	0	0	19	8	22	7	10	9
(*b*) Rectifiers	1	14	21	7	9	15	46	36	73	60
(*c*) Battery chargers	1	2	5	2	24	1	4	6	6	5
4. Failure rate per 100,000 unit miles:										
(*a*) Motors	0	0	0	0	11	6·2	7·6	1·8	2·8	1·8
(*b*) Rectifiers	3·9	39	42	19	5·1	12	16	9·3	16·0	11·8
(*c*) Battery chargers	3·9	5·6	10	5·5	13	0·8	1·4	1·5	1·3	1·0

Section XIII. Technical Investigations and Action Taken to Correct the Faults in the North-East London Units

Introductory

206. In this section I have summarised the initial investigations, and I bave added notes on the further action taken since the presentation of my second interim report. This section is divided into the following heads:

(*a*) Transformers.

(*b*) Rectifiers.

(*c*) Traction motors.

(*d*) Other modifications.

(*e*) Air-blast circuit-breaker operation.

Transformers

Failures during trial running

207. During trial running on the North-East London lines, the constant blowing of the tertiary fuses in some units led to the examination of three transformers during September, 1960. It was found that the internal connections of the tertiary windings had been seriously distorted and had touched the sides of the transformer tanks, thus causing the faults to earth which had blown the tertiary fuses. None of the windings bad broken down and there was no noticeable disturbance or displacement of the conductors. Stronger clamping screws were provided, and tbe supports of the winding connections of all the transformers were strengthened before the first public service began on 14th November on the North-East London lines.

Other failures

208. Three other failures bave been associated with the North-East London transformers. Flasbovers occurred in the tap changers of transformers 444 and 433 on 22nd December, 1960, and 21st January, 1961, respectively. In the first case tbe tap changers were extensively damaged by a sustained short circuit. Some of the end turns of tbe secondary coil assembly were also displaced, but the strengthened clamp supports were undisturbed.

The flashover in the second transformer had cleared more quickly and there was less damage. Some of the secondary conductors were very slightly twisted but there was no evidence of winding distortion, or of clamping displacement. Mr. Lane concluded that the sustained fault on the first transformer was exceptional and that the damage to both transformers was not such as to throw doubt on the satisfactory performance of the other transformers in service.

209. On 28th April, 1961, the transformer in unit 519 failed in service; this transformer and four others were examined. The failure of transformer 519 was traced to the breakdown of some of the turns in one coil of the secondary winding wbere a section of the turns had been burnt away by the resulting sbort circuit. Some of the secondary connections had also been short-circuited and partially burnt away where movement of the connections had abraded the insulation.

There was some slight displacement of the secondary turns in two of the other four transformers, and the tap connections in all of them had moved slightly. None of the primary windings was damaged. The displacement of the turns in the secondary winding and the movement of the tap connections indicated that the transformers had been subjected to severe electro-magnetic forces, resulting from short circuits caused in the main by rectifier backfires.

Transformer tests

210. A transformer which had not been in service was subjected to a short circuit test of seven shots, some symmetrical and some asymmetrical. This caused the crushing of some of the turns of the primary winding, the overriding of some of the turns in one coil and the displacement of turns in both coils of the secondary winding, as well as the movement of some tap connections. The test was not conclusive, however, because of an error in the test plant connections, and it was decided to carry out a further test on another transformer.

211. On 29th May, 1961, transformer 505 was subjected to a series of 12 short circuits; the first asymmetrical of 4·5 seconds duration was followed by 11 each of approximately 1 second duration—six asymmetrical and five symmetrical.

On examination it was found that some of the turns of the primary winding of transformer 505 were crushed in a manner similar to the damage sustained by the other transformer subjected to the sbort circuit test. Tbere were signs of movement of the coils in both limbs of the secondary winding. This damage was similar, but not so severe, as that suffered by transformer 519.

This test indicated that the failure of transformer 519 could not be regarded as exceptional, and it was almost certainly the result of the onerous treatment to which it had been subjected from repeated

rectifier backfires. No more transformers have failed in service hut some may have heen subjected to similar treatment and may have had their windings overstrained. Since these transformers cannot be repaired without rewinding, Mr. Lane has recommended that they should be rewound so as to ensure satisfactory performance in future.

Rectifiers

Early troubles

212. The rectifier troubles began during trial running and they have persisted throughout. In the early days numerous rectifier cylinders were examined but nothing could be found wrong with them. By the end of 1960, however, it was realised that something was radically wrong with the rectifier design and that the continued failures could no longer be associated with initial " teething " troubles. The position was reviewed during the meeting on 8th January, 1961, and it was thought that some of the rectifier troubles were associated with transient over-voltages. It was decided to continue laboratory investigations and also to carry out further tests to ascertain the cause of the troubles; these were undertaken in conjunction with the running of the test train, but it was difficult to obtain positive results.

The first modifications

213. Eventually the failure of the main anode and the loss of vacuum was traced to fatigue failure resulting from high thermal stresses. A modified form of anode was designed which was expected to stop the loss of vacuum.

It was found in the course of the test train trials that flash-arcs, i.e., backfires of a duration of less than one ½-cycle, frequently occurred when trains were left standing for long periods with the rectifiers energised but not passing load current. It was decided to modify the power circuits so that they were physically interrupted when the controller was in the " off " position, thus ensuring that the rectifiers were always disconnected when the equipment was idle.

The Contractors considered that the flash-arcs were caused hy mercury condensation which could be cured by keeping the anode hot, and they decided to provide dual cooling whereby the eight anodes were in one cooling circuit and the eight cathodes in the other. By this means it was expected that a suitable temperature difference could be maintained in the rectifier under all conditions.

The three modifications noted above formed part of the " C " modifications.

Half-wave rectification

214. The Com-Pak rectifier was so designed that it would be automatically re-ignited each time the voltage in the excitation circuit was reduced excessively or lost. There was a limit of four or five re-strikes that could be made in rapid succession after which the excitation might " lock out ". The recovery time varied according to the condition of the individual rectifier, thus when a series of break/make operations of the air-blast circuit-breaker (A.B.B.) occurred in rapid succession it was possible for some rectifiers to remain excited and others to become unexcited; this condition set up what was known as " half-wave rectification ", i.e., the normal D.C. motor current was changed into a pulsating half-wave current. It was considered that these conditions produced the highest voltage surges through the motor circuits.

On some occasions as many as 14 successive disturhances were recorded as a result of pantograph "bounce" on a "hard" section of the overhead equipment. I therefore recommended that consideration should be given to re-desiging the excitation gear so as to increase the number of re-strikes which could be made in rapid succession and thus eliminate rectifier " lock out ".

Further investigations

215. The above was the position when I presented my second interim report on 30th May, 1961. Since then attention has been concentrated largely on removing the faults which still existed in the Com-Pak rectifier. This has heen a long and difficult task, largely on account of the complex nature of the rectifier, on its small size and on the limited space available for housing it and its auxiliary equipment under the floor of the motor coach. A number of unusual problems required solution, and these are described below.

Rectifier anodes

216. All the rectifiers have been fitted with a new and stronger anode capable of withstanding all normal stresses. A number have failed, however, on account of the melting of the anode due to restricted flow and, in some cases, total loss of cooling liquid. It was concluded that the new anode needed no alteration but that the cooling problem had still to be solved.

Dual cooling

217. Dual cooling whereby the eight anodes and the eight cathodes are cooled separately has involved the complete rebuilding of the rectifier cooling equipment and the provision of a second circulating

pump together with thermostats to control the upper and lower temperature limits in the two cooling systems. The modified rectifiers, however, continued to fail at an undesirably high rate, and almost all of the failures were directly attributable to some failure of the cooling system.

Cooling hoses

218. When the North-East London units first began running, the rectifier cooling system was equipped with Nitrile rubber hoses. After some months these deteriorated due to the effect of atmospheric ozone. Experiments were made with Neoprene hoses which resisted ozone, but these failed electrically and as a result a number were burnt and punctured. An anti-ozonant paint has now been applied to the Nitrile hoses to extend their life. Meanwhile the Contractors have continued their researches and have produced new types of hose which they expect will remove these sources of trouble.

The elimination of the hose failures, even temporarily, did not solve the cooling problem, and further investigations showed that the ferrules of some of the hoses were becoming blocked with a deposit formed by electrolytic action. The hoses are small and hence a small deposit is sufficient to restrict seriously the flow of cooling liquid.

Since this became known an intensive programme of hose cleaning was instituted. This has reduced the rectifier failure rate, but it has seriously increased the maintenance problem. Further research has indicated a solution and a new device to prevent corrosion has been given laboratory tests.

Excitation equipment

219. Excitation was originally controlled by selenium auxiliary rectifiers, but these were unable to withstand the high voltage surges in the tertiary circuit, combined with high ambient temperatures. The high voltage surges have been reduced and the selenium rectifiers have been replaced by silicon rectifiers capable of withstanding higher voltages.

The redesign of the excitation gear to increase the number of re-strikes and so eliminate " lock-out " of rectifier excitation has proved most difficult, and a satisfactory solution has not yet been found. The improvement in the overhead line at the places where troubles were experienced, and the slowing down of the A.B.B. opening under normal power interruption conditions (*see* paragraph 232) have eased the problem to such an extent that the modification of the excitation gear became no longer necessary.

Traction Motors

Early troubles

220. No motors failed during trial running and none failed during the week of limited public services from 14th to 20th November, 1960, but when the full intensive service on the faster timings began on the next day the first motor failure occurred, and this was followed by many others.

The failures were confined principally to traction motors in the 3-car units operating on the Chingford and Enfield lines energised at 6·25 kV. In almost every case earth faults had occurred at one or two places in the motor field and/or interpole circuit. In all cases the coils and the associated details had been severely damaged.

" A " Modifications

221. On 14th December, 1960, a series of modifications, known as the " A " modifications, was agreed. It included the fitting of new surge absorbers across the motor chokes and the checking and adjusting of the overload relays.

Further investigations

222. These modifications did not prove adequate and on 8th January, 1961, a meeting was held between the Commission's Engineers, the Consulting Engineers, and the Contractors, at which the Contractors stated that they had come to the conclusion that most of the motor troubles arose from transient over-voltages developed by the air-blast circuit-breaker " chopping " on the 6·25 kV lines. They believed that these over-voltages created surges in both the secondary and tertiary circuits of sufficient magnitude to cause not only the failures of the motors, but also of the rectifiers and the battery chargers.

It was decided to make a detailed examination of the effect of these transient over-voltages, and the Contractors announced that they would equip a train as a mobile laboratory for use in carrying out all necessary tests. A description of this train and the results achieved with it are given in the Appendix.

" B " Modifications

223. It was also decided to make another series of modifications, known as the " B " modifications. These included the provision of an earth and an earth fault relay at the mid-point of the motor circuit instead of the earth at the mid-point of the transformer winding, and the insertion of a 10 k/ohm resistor

to earth at the mid-point of the transformer secondary circuit. Three diverters were also to be fitted at three points in the transformer secondary circuit. These modifications were completed by 16th March, 1961.

" C " Modifications

224. As a result of the information obtained from the test train, further modifications, known as the " C " modifications, were recommended, and these are described separately in paragraph 226, because they affect not only the operation of the motors but also other electrical equipment.

Final results

225. All these modifications have been made but a few motors have since failed as can be seen from Table 18. There have, however, been no more main field coil failures though in a few cases the interpole coils have short-circuited to earth; in addition further armature failures have occurred. These failures are attributed in the main to the long term effects of the earlier voltage surges, and there is no reason to doubt that the modifications have been effective in reducing substantially the over-voltages that were impressed on the motor circuits.

Other modifications

" C " Modifications

226. In my second interim report I recorded that a number of modifications were still to be made to the power circuits so as to reduce the effect of voltage surges and to protect the traction motors. They formed part of the " C " modifications and included the following:

(*a*) Provision of a protective capacitor/resistor network across the transformer secondary winding.

(*b*) Provision of a spark-gap device for the motor smoothing choke.

(*c*) Replacement of overload relay No. 3 by one of improved type.

Capacitor/resistor network

227. A capacitor/resistor network has been incorporated in the secondary circuit. A five microfarad condenser has been fitted across the secondary winding with a 20 ohms resistance in series with it. This modification has been effective in reducing the overload voltages through the secondary and tertiary circuits.

Motor smoothing choke

228. A new type of diverter of much greater thermal capacity than the original has been fitted to all units in service, and is operating successfully.

Overload relay No. 3

229. An improved type of relay has been provided.

Battery chargers

230. The selenium auxiliary rectifiers of the battery chargers have been replaced by silicon semi-conductors which can withstand higher voltage surges.

Automatic power control and air-blast circuit-breaker control

231. Other modifications included the addition of a voltage lock-in relay to the automatic power control (A.P.C.) equipment so as to lock the changeover switch in the 25 kV position until released by the relay, which responds only to the track magnets of the neutral sections. This has been done as a result of the investigations into the operation of the A.P.C. of the Glasgow train units (*see* paragraph 146).

232. A delay of 0·1 second has been applied to the opening of the A.B.B. but under fault conditions the speed of opening of the breaker has not been affected. This has reduced the number of A.B.B. operations resulting from a rapid succession of pantograph " bounces ".

Air-blast circuit-breaker operation

233. Most of the troubles experienced with the traction motors and battery chargers and other auxiliary equipment have been the result of high transient over-voltages developed by the opening of the air-blast circuit-breaker when operating on the 6·25 kV lines. The effect of these over-voltages has been reduced by the application of various remedial measures, as already described, but so far no modification has been made to the A.B.B. itself in order to reduce the over-voltages at source.

A device in the form of an auxiliary switch has now been proposed by Messrs. Merz and McLellan for use with the A.B.B.; it has the effect of connecting a resistance across the primary side of the

transformer before the A.B.B. is opened. A prototype has been made and tests have established that this device will reduce over-voltages when " chopping " on either 25 kV or 6·25 kV lines to the order of 25 per cent. above the normal operating voltage on either line. Such a device should reduce appreciably the danger of breakdown from switching over-voltages.

Section XIV. Conclusions and Remarks on the Failures of the North-East London Multiple-Unit Trains

234. In my second interim report presented on 30th May, 1961, I stated that the chief causes of trouble with the North-East London units were the failures of traction motors, rectifiers and battery chargers, and that shortly before my report was completed the failure of transformer 519 threw some doubt on the future performance of this piece of the equipment.

Transformers

235. As the result of a further transformer test, Mr. F. J. Lane concluded that the failure of transformer 519 could not be regarded as exceptional and that there was the possiblity of similar types of failure occurring in service. I accept Mr. Lane's conclusion and his recommendation that all the transformers should he rewound so as to ensure their satisfactory performance in the future. The modified design depended upon the type of rectifier to he used, and now that silicon diodes are to replace the mercury arc rectifiers, the modifications have heen finalised though the rewinding of the transformers has not yet hegun. The transformers have, however, functioned satisfactorily, even though they have been subjected to short circuits from backfires, and Mr. Lane has no reason to think that any will fail in service before they are rewound.

Rectifiers

236. The fundamental causes of the failure of mercury arc rectifiers had not been conclusively established when I presented my second interim report. Mechanical failure and unsuitable cooling arrangements appeared to have been the major causes of trouble, though the failure of the auxiliary ignition and excitation rectifiers from over-voltages in the tertiary circuit was a contributory factor.

Much effort has been spent since then in applying the various remedies recommended hy the Contractors, and at the present time the rectifiers are giving a better performance in the prevailing low ambient temperatures. They are, however, complicated pieces of equipment with duplicate circulating pumps and no less than five thermostats to control the temperature limits. They are mounted in a confined space under the floor of the motor coach, and at present they require excessive maintenance. The Commission have therefore asked the Contractors to replace them by silicon semi-conductors. I consider that this is a wise decision as I have little doubt that these semi-conductors, which have already proved their worth in other units, will give a more reliable service than the mercury arc rectifiers in the G.E.C. units.

Over-voltages

237. Mr. E. L. E. Wheatcroft bas confirmed tbat the breakdown of the traction motors and of the battery chargers and other auxiliary equipment in the tertiary circuit was caused primarily hy the severe transient over-voltages developed by the air-blast circuit-breaker " chopping " on the 6·25 kV lines. The effect of these over-voltages on the secondary and the tertiary windings is some four times greater on the 6·25 kV lines than on the 25 kV lines, because the over-voltages are largely determined hy the inherent characteristics of the air-hlast circuit-breaker, and they are approximately the same when operating on either voltage. Surges up to six and seven times the normal peak were recorded with the test train.

The most serious effects were caused by the A.B.B. " chopping " when the normal D.C. motor current was changed to a pulsating " half-wave " current by the temporary loss of excitation of some of the rectifiers. This phenomenon arose when pantograph " hounce " occurred so frequently that some of the rectifiers were no longer able to re-ignite.

238. The effect of the over-voltages has been substantially reduced by providing surge diverters and a capacitor/resistor network across the secondary winding. The number of A.B.B. operations resulting from a rapid succession of pantograpb " bounces " has also heen reduced hy retarding the opening of the breaker.

239. Alterations have also been made to the overhead equipment at those places where pantograph " hounce " had been particularly prevalent. In Clapton Tunnel for instance, where the chief troubles were experienced, current collection has been much improved by a realignment of the overhead equipment.

240. Even with these improvements some transient over-voltages will still be impressed on the secondary and tertiary windings when operating on the 6·25 kV lines because the rate of operation of the circuit-breaker cannot be altered without complete redesigning. The moving of the earth point of the secondary circuit to the mid-point of the motor circuit has, however, provided adequate protection for the traction motors, whilst the selenium rectifiers used in connection with the battery chargers and main rectifier excitation have been replaced by others capable of withstanding the maximum voltages which can still be impressed on the tertiary circuits.

These remedial measures have solved the problem of controlling the excessive voltages produced by the circuit-breaker " chopping " on the 6·25 kV lines. A more satisfactory solution would be the reduction of these over-voltages at their source.

Air-blast circuit-breakers

241. As I have mentioned in paragraph 233, an auxiliary switch has been proposed by Messrs. Merz and McLellan which has the effect of reducing to negligible proportions the excessive voltages generated by the A.B.B. when " chopping " on either 25 kV or 6·25 kV lines. Tests with a prototype have been promising and I hope that this or some similar device can be developed so as to eliminate completely any danger of breakdown from switching over-voltages. It may also lead to the removal of some of the palliatives which have had to be applied to cope with such severe electrical stresses.

PART V. EXPERIENCE WITH THE OTHER MULTIPLE-UNIT TRAINS AND THE A.C. ELECTRIC LOCOMOTIVES

SECTION XV. REVIEW OF THE RUNNING OF THE LONDON, TILBURY AND SOUTHEND ELECTRIC MULTIPLE-UNIT TRAINS AND THE SHENFIELD AUGMENTATION STOCK

The London, Tilbury and Southend units

Trial running

242. The units destined for the London, Tilbury and Southend (L.T.S.) services are fitted with electrical equipment supplied by the English Electric Company. The design of this equipment was based on four years' operating experience on the Lancaster–Morecambe–Heysham line (*see* paragraphs 91 to 93), as well as research into the dual voltage system.

243. The first of the new units arrived on the Styal line in October, 1958, and after testing, it began trial running in December; this and other units were used largely for training motormen and maintenance staff until they were later transferred to the Colchester–Clacton lines where the first unit began running in February, 1959.

In July, 1959, another unit began running on the Glasgow suburban lines where a short length of line energised at 6·25 kV was available, and it was followed by three more in October. These units were also used principally for the training of motormen, and they were returned to the Colchester–Clacton line in February, 1960; they performed very satisfactorily in Scotland and there were only a few minor troubles to correct. Meanwhile further units were sent to the Colchester–Clacton line until by October, 1960, the whole fleet of 112 units had been commissioned and tested there. But for the four units used in Scotland all the running up till then had been on lines energised at 25 kV, though the A.P.C. equipment of each unit was tested at the two specially equipped neutral sections between Alresford and Thorington.

244. This A.P.C. equipment operated incorrectly once in November, 1959, when a unit was on test. A capacitor divider failed from internal short circuit and caused the voltage changeover switch to change to the 6·25 kV position, thus subjecting the transformer momentarily to four times its normal voltage. The primary overload relay opened immediately and brought out the circuit-breaker.

The transformer was examined and found to be completely undamaged in spite of this severe treatment.

245. Some minor troubles were experienced, but generally the equipment gave excellent service. The transformers were very reliable, the main mercury arc rectifiers functioned well, and there were few backfires. The traction motors also gave very little trouble at this time, and their performance and commutation were satisfactory. There were a few minor failures of the battery charger equipment but nothing comparable with those which occurred later when running on the 6·25 kV lines (*see* paragraph 251).

Service running

246. The L.T.S. units began operating a public service on the Colchester–Clacton lines in March, 1959, whilst trials were still in progress, and in November, 1960, the first of these trains was introduced on the North-East London suburban service.

Pantograph and air-blast circuit-breaker (A.B.B.)

247. Loss of contact between the pantograph and the overhead wire was noted at a number of places. The maximum recorded number of successive bounces has been six. Over-voltage surges were produced as a result of the A.B.B. " chopping ", but so far the maximum recorded when working on the 6·25 kV line has been 47 kV. Although no cases of a circuit-breaker failing to open have been reported with this stock, the Brown Boveri lock-in device has been removed.

Automatic power control equipment

248. On 23rd January, 1961, an accident occurred at Roydon when a capacitor divider exploded and blew in the cover plate on which it was mounted, injuring the guard in the compartment below. Following the accident a large number of other capacitor dividers were subjected to an over-voltage test equivalent to four times the normal peak load. None of these capacitors failed from the test and less than 2 per cent. of the individual elements developed faults. It was considered that the Roydon failure was a random one. To prevent similar danger in the future, the cover plate has been strengthened and the capacitor is now mounted on a stronger base and with an explosion diaphram at the top to release any blast in the rare event of another capacitor failure.

Transformers

249. The transformers which have pancake windings have given excellent service and no troubles have been experienced with them, although at times they have been subjected to backfires and to high transient over-voltages when operating on the 6·25 kV lines, in addition to the severe electrical stresses produced by the occasional impressment of 25 kV on the 6·25 kV winding. One such transformer was returned to the Contractor's Works for examination and found to be in excellent condition.

Rectifiers

250. The rectifiers have given very satisfactory service; there have been occasional backfires and some difficulties with excitation, but nothing significant.

Auxiliaries

251. The battery chargers which were of the same design as those fitted to the North-East London units, also suffered from similar breakdown, and at one time their failure rate was comparable to that of the North-East London battery chargers. The L.T.S. units have capacitors fitted across the tertiary windings and it was hoped thereby to retain the original selenium rectifiers, but during severe weather conditions moisture penetrated into the cells; these will be changed for others less vulnerable in this respect.

Traction motors

252. But for some initial overheating on account of overloading by using 4-car units in emergency on a duty for which 3-cars was the maximum permissible load, the traction motors gave good service when the L.T.S. units were first introduced on the North-East London suburban lines. After the first four months, however, a number of motors began to fail on account of a breakdown of the insulation in the armatures, the interpoles and the main field coils. This was due to technical difficulties and manufacturing faults.

253. The faults were noticed during manufacture but not until 75 per cent. of the traction motors had been completed. It was hoped that modifications could have been made before their breakdown in service, but the failures developed at too high a rate and an emergency programme was prepared to get these motors rewound with the minimum of delay with modified armature cores and improved coil insulation. It should be pointed out that the underlying cause of these unfortunate failures was in no way connected with the operation of the motors on the A.C. system, and they were never of sufficient magnitude to disrupt the services on which the units were working.

The Shenfield augmentation stock

Introductory

254. In addition to 112 units for the London, Tilbury and Southend service, 42 units, known as the Shenfield augmentation stock, were ordered for use on the Liverpool Street–Shenfield–Chelmsford and Southend (Victoria) lines and on the Colchester–Clacton lines if so required. They are 4-car units and they were built in the British Railways' workshop at York with electrical equipment supplied by the English Electric Company. This equipment is very similar to that in the L.T.S. units, but the mercury arc rectifiers have been replaced by silicon diodes made by the Westinghouse Brake and Signal Company.

Trial and service running

255. The first unit began trial running on the Colchester-Clacton lines on 25th February, 1961, and up to 31st December, 1961, all 42 units had been tested and had run for 54,100 miles on trial. These units were transferred to the Liverpool Street–Shenfield–Chelmsford and Southend (Victoria) services as soon as they had completed their tests. Up to 31st December, 1961, they had run nearly 1½ million miles in public service.

Operation experience

256. These units have functioned excellently in all respects. The motors have given little trouble; the transformers, like those in the L.T.S. units, have performed impeccably, and the silicon rectifiers have shown by their reliability, their freedom from backfire, and their easy maintenance that they are more suitable for electric traction than their mercury arc counterparts.

257. The lock-in devices on the Brown Boveri circuit-breakers of these units have also been removed, but recently an A.B.B. failed to open on account of an intermittent mechanical fault. On fifteen occasions the unit ran through a 6·25/25 kV changeover neutral section with the breaker closed. Each time 25 kV was impressed on the 6·25 kV windings of the transformer and the fault was not cleared until the overhead line breakers opened; fortunately these responded rapidly. In spite of this exceptionally severe treatment only the battery charger was damaged.

258. Of the auxiliaries, the battery chargers, though of the same type as those installed in the North-East London and L.T.S. units, have given little trouble until recently. They also were affected by very severe winter weather and are to be changed for others less vulnerable in this respect.

Section XVI. Experience with the Converted Stock Running on the Electrified Lines in the Eastern Region

Introductory remarks

259. The Liverpool Street–Shenfield–Southend (Victoria) line and the short extension from Shenfield to Chelmsford were originally electrified on the 1,500 volts D.C. overhead system. Prior to the opening of the North-East London surburban A.C. electrification, the line to Southend (Victoria) was converted to the A.C. system at 6·25 kV and later the extension to Chelmsford was converted to A.C. at 25 kV with a voltage changeover neutral section at the country end of Shenfield Station.

260. The 3- and 4-car multiple-units also had to be converted for A.C. operation. The existing D.C. motors with their conventional D.C. series-parallel control were retained, and the other equipment for A.C. operation was supplied by A.E.I. (Manchester). It included new circuit-breakers, the automatic power control equipment, transformers and germanium semi-conductor rectifiers. Brief particulars have been given in the tables in Section IV to enable a comparison to be made with the other types of equipment now in use.

261. The converted stock was tested on the Colchester–Clacton 25 kV lines and units began running on the Shenfield and Southend (Victoria) lines after they were converted to 6·25 kV A.C. operation in November, 1960. The units gave excellent service on the 6·25 kV lines but for some difficulties with the rectifier ventilation equipment when passing through the carriage washing plant at Ilford. Water and acid were sprayed into the air inducts and thence were drawn through the rectifier trays causing insulation and cell failures. The trouble was cured by altering the position of the air intake, but further difficulties of a temporary nature arose when operating in snow.

262. In March, 1961, the Shenfield–Chelmsford extension was electrified at 25 kV and no troubles of any consequence were experienced until 29th May when an air-blast circuit-breaker failed to open while the train was passing through the Shenfield voltage changeover section, and this caused a serious failure of the transformer. Several other such failures have occurred at the same place and these are described in the paragraphs that follow.

Transformers

The first accident

263. On 29th May, 1961, shortly after passing through the Shenfield voltage changeover neutral section, the guard of a 9-car Liverpool Street–Chelmsford train saw black smoke passing his window and promptly stopped the train. On examination it was found that the transformer and choke tanks of unit 015 were bulged, and the cover of the voltage changeover switch chamber had been partially blown off. The coach paint work was blistered and the windows were cracked by the heat, but no one was injured.

Oil and packing pieces from inside the transformer were found on the track 400 yards from the neutral section exit track magnet, and traces of transformer oil were found for a further ¼ mile up to the point where the train stopped.

The unit had only been in service for four days since its conversion to A.C. The cause of the accident was traced to the failure of the air-blast circuit-breaker to open when passing through the changeover neutral section, thereby causing 25 kV to be applied to the transformer windings when they were still set for 6·25 kV operation. The circuit-breaker failed to clear when the consequential short circuits occurred in the equipment, and current was finally cut off by the opening of the line circuit-breaker.

The other accidents

264. On 5th July a second transformer in the unit of an empty stock train failed from a similar cause and on the next day there was a similar accident also in an empty train. The next incident was on 2nd August and the last on 6th November, 1961, when a transformer failed in a passenger train and a small fire that broke out was dealt with by the train crew. Meanwhile on 29th September another circuit-breaker failed to open when passing the Shenfield neutral section, but this fault cleared itself before serious damage was done.

Damage to the transformers

265. The five damaged transformers all suffered similarly. The tank and choke covers were buckled and the covers of the voltage changeover switch chambers were blown open. The leads from the primary winding were distorted and burnt and most of them had short circuited. The primary windings themselves were distorted and forced outwards from the core, and in some cases the turns were burnt and broken. The tertiary windings which are wound between the layers of the primary windings were badly distorted and burnt. The secondary windings which are next to the core were also badly distorted, and in a few places electrical failure had occurred from the breakdown of the paper insulation by mechanical disturbance.

Couse of the damage

266. It should be noted at this stage that these transformers have no tap changers on the secondary winding because the original D.C. motors are controlled by cutting out successive steps of starting resistance and then using weak field connections in accordance with conventional D.C. practice. Hence the full secondary winding is connected permanently across the bridge-connected germanium rectifiers, each of which is protected by an H.R.C. (high rupturing capacity) fuse. On the application of excess voltage the excess current that flowed caused these fuses to blow, and being subjected to excessive over-voltage they exploded.

Examination of the damaged units showed that these fuses on exploding had caused arcs to flash across to the earthed rectifier frame. These set up sustained short circuits across the transformer secondaries because the A.B.Bs. could not trip in response to the operation of the secondary overload relays.

267. The excessive voltage applied to the primary also caused excessive voltage to he impressed on the tertiary circuits, resulting in the tertiary H.R.C. fuses also exploding. These are located in the transformer L.V. terminal compartments, and the arcs produced hy the exploding fuses caused short circuits across the tertiary windings.

Thus sustained short circuits were placed simultaneously across the secondary and tertiary windings, and the resulting excessive electro-mechanical and thermal stresses caused their complete collapse.

The collapse of these windings and the failure of the primary winding transferred the faults to the primary side, and these were not cleared until the fault current in the overhead line operated the track feeder circuit-breakers or burnt through the line, as happened on two occasions.

268. Although all the windings must have been heated rapidly by the high short circuit currents, only the tertiary winding insulation was seriously damaged by heat. These windings probably collapsed first causing the copper conductors to break and set up arcs in the transformer oil which decomposed very rapidly and released quantities of gas.

The 1-in. bore pipe leading to the conservator tank was not large enough in these circumstances to release the gas before the pressure inside the tank caused the cover to bulge and so allow the hot gases and oil to escape freely. The burning gas and oil extinguished itself very quickly and on only one occasion did the oil continue to burn until extinguished by motormen.

The failure on the 29th September

269. The failure on 29th September was of a somewhat different character. On this occasion the A.B.B. failed to respond to the A.P.C. selector relay when it passed over the first track magnet of the Shenfield voltage changeover section, and hence the changeover switch remained in the 6·25 kV position when the pantograph passed on to the 25 kV line. The resulting over-voltages caused a short circuit in the secondary circuit from exploding fuses as on other occasions, but this time the A.B.B. tripped at once in response to the operation of the secondary overload relay.

The tertiary winding also did not suffer damage on this occasion because the A.C. operated battery charger had not yet been fitted to the unit, and as a result the load through the tertiary fuses was not sufficient to explode them and so short circuit that winding.

Circuit-breakers

Causes of mal-operation

270. All six incidents described in the preceding paragraphs were caused by the circuit-breaker remaining closed when passing through the Shenfield 6·25/25 kV voltage changeover neutral section, and all were the result of different faults.

On the first occasion the breaker failed from mechanical seizure, primarily on account of lack of lubrication during assembly. The next failure occurred when the control arm became loose and jammed the magnet valve. The third was caused by some fault that cleared itself and could not be traced afterwards.

Twice foreign objects lodged on terminals in the low voltage compartment in the guard's van and short-circuited some of the A.B.B. controls. On the last occasion a pipe joint became loose after it had been adjusted and as a result the air supply to the blast valve was insufficient to open the A.B.B. This fault occurred between the A.B.B. governor (see paragraph 64) and the blast valve; hence the former was not affected and could not open the breaker when the air pressure in the valve fell too low to he effective.

Action taken

271. It is remarkable that these failures which caused such severe damage to the transformers, and which might have resulted in injury to passengers, stemmed from different types of fault, but none was fundamental. Prompt steps were taken to deal with each one in turn and a number of minor

modifications have been made to the circuit-breaker. Until the effectiveness of tbese modifications has been proved and the reliability of the circuit-breakers thoroughly confirmed, a watcb is being kept on all units passing through the Sbenfield voltage changeover section so that immediate action can be taken should any breaker remain closed again.

272. Twelve breakers of similar type that were fitted to the Glasgow units bave been replaced by another type, though none of tbem failed whilst operating the Glasgow suburban services. The 10 breakers fitted to the A.E.I. locomotives working on the Crewe–Manchester service are still in use but they bave been modified. These locomotives work only on the 25 kV line and the voltage changeover switch is locked for the higher voltage; there is no question therefore, of this voltage being impressed on the 6·25 kV connections of the transformer, sbould a circuit-breaker fail to open.

Section XVII. Experience With The London Midland Region Multiple-Unit Trains and Electric Locomotives

Introductory

273. As already explained the Crewe–Manchester main line and the Styal line are both electrified at 25 kV; consequently the dual voltage system has not been in operation and the electrical equipment has not been subjected to severe transient over-voltages from circuit breakers " chopping " on the 6·25 kV lines as has occurred in the Scottish and Eastern Regions. For most of the time the automatic power control system on both the multiple-units and the locomotives has been locked with the change-over switch in the 25 kV position; thus the equipment has not been influenced by induced voltages and similar phenomena such as affected to some extent the Glasgow multiple-unit equipment. Before the decision was taken to lock the A.P.C., one incident of irregular voltage changeover was reported and referenee is made to this in paragraph 285.

274. Tbe Crewe-Manchester line is the first higb speed main line to be electrified with trains running at speeds up to 90 m.p.h., and it includes the exceptionally busy and extensive junction at Crewe where large numbers of steam locomotives still operate. It is, therefore, of interest to compare not only the performance of the multiple-units and locomotives operating on these lines with that of the multiple-units in the Scottisb and Eastern Regions, but also to note some of the problems which have arisen in connection with tbe overhead equipment.

Overhead equipment

275. Some trouble from pantograph " bounce " has been experienced at neutral sections where multiple-units and locomotives have run at maximum speeds up to 90 m.p.h. This has been overcome by changing the porcelain insulators of the carrier wire type of neutral sections to fibre glass insulators coated with P.T.F.E., and by making otber associated modifications.

Under bridges where tbe minimum clearance only could be provided, hard spots in the overhead equipment caused pantograph " bounce " at the higher speeds, and relays and other protective devices on the motive power units did not always respond quickly enough to clear the in-rush current when the pantograpb remade contact. Tbese difficulties have been overcome by improved devices on the power units whilst improvements in the design of the overhead equipment are being developed as a result of the valuable experience that has been gained.

276. At Crewe where there is very heavy smoke pollution from the continued use of steam locomotives, flasbovers across insulators have occurred, especially in misty and foggy weather wben the atmosphere becomes particularly dense and moist. Tbese difficulties have largely been overcome by developing new types of insulator, fitting arcing borns, and coating insulators with a silicon grease which improves tbeir resistance to flashovers and makes cleaning easier. An improved type of line relay has also been introdueed to clear line faults arising from flasbovers and other causes mucb more quickly than with the original relays.

The multiple-units

Trial and service running

277. As already described in paragraph 99, trial running began on the Styal line in April, 1960, and 15 units were available to operate the public serviees on 12th September, 1960. Since then the complete fleet of 45 units needed for both the Crewe–Mancbester and Crewe–Liverpool electrifications have been delivered, of whicb 38 units have been commissioned.

Up to 31st December, 1961, the multiple-units had run 41,000 miles on trial and over 1 million miles in public services on the London Midland lines. Three units, of which one has since been returned, were loaned to the Eastern Region wbere they have operated on the Liverpool Street–Southend (Victoria) line wholly electrified at 6·25 kV and on the North-East London suburban lines electrified partly at 6·25 kV and partly at 25 kV. The three units bad run for 195,000 miles up to 31st December, 1961.

278. It will be noted that the units loaned to the Eastern Region have run a much higher mileage per unit than those operating on the London Midland lines. This has been on account of the comparatively light passenger services which the latter had to work, and the large number of units available. Hence no operational difficulties were experienced in withdrawing units from the London Midland line for modifications or adjustment. Much of the public service running has in fact been trial running and has enabled modifications and improvements to be tested without difficulty.

Transformers

279. The contactors have given some trouble but there has been only one failure; this resulted from a contactor finger on the voltage control camshaft having sheared and dropped on to the bottom contactor taps. It welded itself between the top and bottom contacts as well as causing the tips of another contactor to become welded. This caused a short circuit on the transformer secondary tap connections which in turn caused a short circuit in one limb of the secondary winding.

The primary winding and one limb of the secondary winding was undamaged but some of the turns of the outer layer of the secondary winding in the other limb were burnt through. The burning extended to the second layer but it was confined to an area of eight turns only. The tertiary was undamaged.

This failure was initiated by the mechanical fracture of the contactor fingers and was not caused by any electrical or thermal breakdown. It was aggravated by the motorman resetting the A.B.B. several times in quick succession, thereby subjecting the transformer to a number of severe short-circuits after the A.B.B. had correctly tripped on overload following the first short-circuit. There was nothing in the condition of the transformer winding to cast any suspicion on its ability to withstand all the conditions of normal working.

280. As a result of this failure, contactor fingers of an improved design have been fitted, and some modifications have been made to the camshafts.

After the explosion of the Glasgow transformer on 30th October, 1960, larger vents were fitted to the conservator tanks, and following the explosion on 13th December additional ventilation was provided in the equipment compartments which housed them.

Other equipment

281. There have been some cases of pantograph "bounce" resulting in the rapid opening and re-closing of the A.B.B., but nothing of consequence. The voltage changeover equipment has not been used, as all the lines are electrified at 25 kV. No serious voltage surges from circuit-breakers "chopping" have been recorded.

The germanium rectifiers generally have functioned satisfactorily; occasionally fuses have blown prematurely and a modified type has been fitted. Traction motor commutation gave some trouble, but this has been rectified. There have been some minor faults in the auxiliaries, but nothing fundamental.

282. The experience gained in both trial and service running has been valuable, and a large number of modifications and improvements of all types have been applied and others are planned.

Experience on the Eastern Region lines

283. As already mentioned the three units loaned to the Eastern Region have run for much greater mileages proportionately, and have been subjected to more arduous operating conditions, including working on both the single voltage 6·25 kV lines and on the dual voltage system.

The flashover of a tap changer on one unit and some overload trips on another were reported in the early days. Since then the only troubles of consequence have been the failures of battery chargers and other auxiliary rectifiers of the semi-conductor type on account of high transient over-voltages in the tertiary circuits, such as have been experienced with all units operating on the dual voltage system. The auxiliary rectifiers are being replaced by others capable of withstanding higher voltages.

The A.C. locomotives

284. The locomotives have generally speaking given satisfactory service but, like the multiple-units, they have not yet been subjected to any arduous service because the numbers available are sufficient not only to operate trains on the Crewe–Manchester main line but also on the Crewe–Liverpool main line which has recently been opened for electric traction, as well as to work trains south of Crewe as sections of the main line to Euston are electrified.

Pantograph "bounce" has at times caused A.B.B. "chopping", both when running at high speed through neutral sections and under low bridges where hard spots have developed on account of the restricted clearances.

285. One incident of wrong voltage changeover occurred at Sandbach where the pantograph was allowed to rise so slowly that it drew an arc and the A.P.C. responded to the reduced voltage and threw the selection switch to the 6·25 kV position. Since then the A.P.C. equipment has been locked in the 25 kV position because the London Midland system is energised only at this voltage.

286. The transformer tap changers on one group of locomotives were not reliable and have been modified, otherwise the transformers of all the locomotives bad given very satisfactory performance.

287. A few of the mercury are rectifiers have been replaced on account of unsatisfactory striking arms. Traction motor commutation in some units was not entirely satisfactory, but this has been improved. Some modifications have been made to the auxiliary equipment.

288. The withdrawal from service of a group of locomotives in January, 1960, which received some adverse publicity, was for convenience only in order to make some modifications and not on account of their failure or unreliability. It will be appreciated that ample locomotives were available for duty and it was, therefore, advantageous to withdraw all at one time for modifications rather tban carry them out piecemeal.

289. As with the multiple-units, very valuable experience has been gained and many improvements bave already been made. Others are planned to make these locomotives even more reliable and efficient.

PART VI. GENERAL CONCLUSIONS, REMARKS AND RECOMMENDATIONS

Section XVIII. General Conclusions

The transformers

290. The transformers in the Glasgow suburban electric trains, though well built of high quality materials and capable of enduring a measure of abnormal treatment, could not withstand the very arduous conditions of service to which they were subjected. Some of the secondary windings were gradually weakened and distorted by the severe electro-magnetic forces produced by short circuits which eventually led to the complete breakdown of four transformers and rendered others unfit for further service. Another transformer failed finally from a severe voltage surge. The transformers have been rewound to a much stronger design.

I have little doubt that the primary causes of these failures were frequent short circuits resulting from the backfiring of the mercury arc rectifiers. The irregular locking in of circuit-breakers during backfires and high over-voltages associated with backfires may have been contributory factors in a few cases, and the overheating of the winding may have caused some damage to two transformers.

The transformers of the North-East London units were severely strained, but not to such a marked degree, by short circuits that were also caused by the backfiring of mercury arc rectifiers.

291. On the other hand transformers with pancake or interleaved windings, as fitted to the L.T.S. and Shenfield augmentation stock and now in the Glasgow units, have withstood severe treatment both on test and in service, including short circuits from backfires.

The modified Glasgow transformer was subjected to 50 short circuits of mixed asymmetry—a test of much greater severity than any ever before applied to a traction transformer. On fifteen occasions a transformer on a Shenfield unit, operating on the newly opened L.T.S. line, had 25 kV impressed on its 6·25 kV winding when a circuit-breaker failed to open on passing through a 6·25/25 kV voltage changeover neutral section; fortunately the line protection cleared the faults rapidly. Both transformers withstood this exceptional treatment unscathed, thus demonstrating the effectiveness of their design and the high standards of material and workmanship in their manufacture.

292. The failures of transformers of the " converted " stock occurred during passage through the 6·25/25 kV changeover neutral section at Shenfield where 25 kV were also impressed on the 6·25 kV windings, when the air-blast circuit-breaker failed to open. The track feeder circuit-breaker was slow to respond to the overload, and on two occasions power was only cut off after the fusing of the overhead wires. The voltage surges exploded the fuses protecting the secondary and tertiary circuits and caused direct short circuits which were sustained until the power was eventually cut off. No transformer could be expected to withstand such stress, and the insulation broke down and severe inter-turn arcing took place. This led to the burning and distortion of the turns, to the gasification of the oil, and to high internal tank pressure.

Rectifiers

293. In the Glasgow and the North-East London units much trouble has been experienced from the backfiring of the main mercury arc rectifiers.

In the Glasgow units the chief causes of backfire were overheating or unfavourable anode/cathode temperature differential. These difficulties have now been overcome and the rectifiers are functioning satisfactorily.

In the North-East London units the rectifiers are liquid-cooled and many of them also became overheated; others failed from loss of vacuum. Dual cooling was provided to maintain a suitable anode/cathode temperature differential but the overheating continued and was finally traced to restrictions in the cooling pipes caused by electrolytic action. Although a cure seems to have been found, the Commission have asked the Contractors to substitute silicon rectifiers similar to those in the Shenfield augmentation stock. This is, I consider, a wise measure because these rectifiers have shown by their reliability, their freedom from backfire, and their easy maintenance to be more suitable for electric traction than their mercury arc counterparts.

Traction motors

294. The failures of the traction motors in the North-East London units were directly attributable to the over-voltages generated by the rapid operation of the air-blast circuit-breaker when " chopping " on the 6·25 kV lines, the most severe results occurring when "half-wave" rectification also developed. Protection was provided by adding additional suppression and by moving the earth point of the

secondary circuit to the mid-point of the motor circuit. On the other hand, the failures of the traction motors in the L.T.S. stock were due to technical difficulties and manufacturing faults in no way connected with the A.C. system.

Transient over-voltages

295. High transient voltages generated as a result of the air-blast circuit-breaker "chopping" on the 6·25 kV lines were sources of trouble in both the Scottish and Eastern Regions. The effect of these voltage surges are some four times greater when operating on the 6·25 kV lines than on the 25 kV lines. This is because the primary over-voltages are largely determined by the inherent characteristics of the air-blast circuit-breaker and are approximately the same when operating on either line voltage, whereas the transformation ratio of the secondary winding is four times greater on 25 kV than it is on 6·25 kV. Surges up to six and seven times the normal peak were recorded in the secondary windings when operating on the 6·25 kV lines. The effect of the over-voltages is transmitted proportionately to the tertiary windings which were thus subjected to similar heavy surges.

Air-blast circuit-breakers (A.B.B.)

296. As already noted, the failures of air-blast circuit-breakers to open when passing through a 6·25/25 kV neutral section in the Eastern Region resulted in one minor and five major transformer failures in the "converted" units. Some of the failures of the circuit-breakers arose from mechanical defect and others from carelessness.

297. In the Glasgow units a different type of fault in circuit-breakers was discovered. It arose from the tendency of the lock-in device to vary its setting within wide limits, depending on the friction in the operating mechanism. It was found that at times this device might operate at a higher air pressure than that at which the governor was set, thus preventing the breaker from opening in response to the governor should the air pressure fall too low for its successful operation.

The lock-in device has now been removed, but its irregular operation may have been a contributory factor in the Glasgow transformer failures, though, as explained in paragraph 140, the chance of damage from this cause was slight.

298. The circuit-breakers in the units running on the Glasgow and Eastern suburban lines are subjected to heavy treatment on account of the many neutral sections through which they have to pass. Each time the circuit-breaker passes through a neutral section it operates twice, and it averages 20,000 such operations in a year; these are in addition to its operation caused by overloads from backfires, pantograph "bounce" and other faults. Consequently, some of the moving parts have worn rapidly and tended to stick; severe loss of air between the governor and the air-blast has had a similar effect on a breaker. The chance of a circuit-breaker failing to open has been greatly reduced but it still exists and special precautionary measures have been taken to avoid danger until further modifications can be devised.

The automatic power control equipment (A.P.C.)

299. The automatic power control equipment, as originally installed, sometimes operated irregularly by turning the changeover switch on the transformer to the 6·25 kV position when the unit was on the 25 kV line. Such faulty operation caused severe over-voltages that damaged the equipment in the tertiary circuit of the Glasgow units, and may have contributed to the transformer failures. Faulty operation of the A.P.C. was noted in units in the Eastern Region, and some of the damage to auxiliary equipment may have been from that cause. The A.P.C. has now been modified so that the chance of wrong voltage changeover has been virtually eliminated.

Auxiliary equipment

300. The severe transient over-voltages undoubtedly damaged the equipment in the tertiary circuits of units of all types operating on the dual voltage system. The battery chargers in all the units suffered from these voltage surges and, although the surges through the tertiary circuits were suppressed to a great extent, they were still too high for the selenium rectifiers and all of these are now being replaced by silicon rectifiers capable of withstanding higher voltages. The auxiliary excitation and ignition rectifiers of the Glasgow and North-East London units also suffered damage, whilst the blowing of fuses in the tertiary circuit sometimes put units out of action and increased the operating difficulties.

The overhead line equipment

301. Irregularities in the overhead line equipment caused pantograph "bounce" in a few places, particularly in the early days of operation. This "bounce" led to circuit-breaker "chopping", but conditions have now been much improved. The hazard that has still to be faced is the danger that can arise from a circuit-breaker's failing to open when passing through a 6·25/25 kV changeover neutral section. In these circumstances the clearance of the fault depends on the operation of the overhead line protection equipment. This was not sufficiently rapid on the Shenfield line to prevent

damage to some of the " converted " units as already described, and modifications to the overhead line protection equipment are needed both here and at other places where similar trouble might be experienced.

The London Midland Region single voltage system

302. In the London Midland Region, where only the single 25 kV system is in use, the services have run continuously without any serious interruptions, though there have been some faults and failures to which any new form of railway traction is liable. It is important to note, however, that ample multiple units and locomotives were available, and hence equipment could be withdrawn for modification without affecting train services.

Trial running

303. A study of Section VI describing the trial and service running of the multiple-units shows that all the early testing was made on a single voltage system and it was not until March, 1960, that a comprehensive section of the Glasgow dual voltage system was available for trial running. The voltage changeover point on the North-East London lines was not ready for use until six months later and on the Colchester–Clacton line a voltage changeover section was used only for testing the operation of the A.P.C. on individual units and not for continuous running.

On the Glasgow lines the experience gained in trial running was sufficient to indicate that severe over-voltages were damaging the equipment in the tertiary circuit, and it was also found that the automatic power control equipment was operating irregularly. Steps had been, or were about to be, taken to cure these troubles when the services were withdrawn in December, 1960.

On the North-East London lines, on the other hand, the effects of transient over-voltages were not appreciated during trial running because insufficient mileage had been run on the lower voltage lines for these troubles to become apparent.

The first Glasgow transformer failed on one of the last days of trial running, but the issue was confused because it was thought at the time that the failure was due to overheating; the fundamental cause did not come to light until later.

Summary

304. A primary cause of trouble was backfiring by mercury arc rectifiers which over-stressed the transformers in the Glasgow and North-East London units. This type of rectifier was the only proven one available when the initial orders were placed, but the rapid development of the silicon rectifier has changed the outlook and with its use short circuits from backfires will no longer arise to be a source of stress to the transformers.

The faulty performances of the automatic power control equipment and the circuit-breaker, associated with the dual high voltage system, have also contributed materially to the difficulties and failures of transformers, motors and auxiliary equipment.

The effect of faults and failures was intensified by running the new units on suburban lines carrying traffic as heavy as any in the world; not only were heavy duties imposed on the stock, but troubles even of a minor kind had immediate repercussions on the services causing much inconvenience and delay to passengers with consequential adverse publicity.

It is worth recording that these circumstances can never arise again, as future orders for British Railways will be based on the Commission's experience of their present equipments, and there will be available large mileages of electrified lines on which new units can be tested.

Section XIX. General Remarks and Recommendations

305. This inquiry into the troubles arising from the introduction on British Railways of the dual high voltage system with automatic changeover has, inevitably, raised a number of major questions.

(i) Was the British Transport Commission justified in adopting this system of electrification?

(ii) Was the dual voltage automatic changeover principle required, and was it a contributory factor in the incidence of breakdowns?

(iii) Were the breakdowns avoidable?

(iv) Have the faults been eliminated?

(v) What has been achieved?

Choice of system

306. As explained in my review in Section I, the Commission's decision was based on economic and technical considerations, including the study of the comparative costs of electrifying the Euston–Crewe–Manchester lines on the 1,500 volts D.C. or the high voltage A.C. system; this showed advantages in

favour of the latter system. Had 1,500 volts D.C. electrification been used, however, as recommended by the Joint Committee in 1951, I believe that the extensive electrification projects planned by the Commission would have been brought into operation smoothly, the serious difficulties experienced in the Scottish and Eastern Regions would have been avoided and a wider field of electric traction might have been covered.

307. On the other hand, the opportunity for developing in this country A.C. traction at industrial frequency would have been lost, probably for ever. This system is now being introduced on railways throughout the world and it offers extensive scope for further technical improvements and developments. Without an efficient home service on which to demonstrate its achievements, the British electric traction industry would have been seriously handicapped in its efforts to retain let alone expand its export markets, and I have no doubt that these national interests played their part in influencing the Commission's decision, which received the approval of the Minister of Transport in June, 1956. At that time it was the Commission's intention to extend electrification eventually to many main lines where the economies of A.C. traction would have been more marked than on suburban services.

308. The decision to adopt the A.C. system was a bold and courageous one, but it posed a number of problems that required a solution before success could be achieved. The technical wisdom of such a course should not be judged, therefore, by the troubles of the past, but by the present satisfactory performance and the bright prospects for future development.

The dual high voltage system with automatic changeover

309. One of the problems in connection with the introduction of the high voltage A.C. system was the provision of adequate clearances for the overhead equipment within the restricted British Railways' structure gauge. This was solved by the adoption of dual voltage with automatic changeover whereby overhead line clearances could be substantially reduced by using a comparatively low voltage of 6·25 kV in place of the standard 25 kV on those routes in and around great cities, such as London and Glasgow, where many low tunnels and bridges made the work of providing full 25 kV clearances both difficult and costly. Furthermore, the clearances needed for the low voltage line were the same as those for the existing 1,500 volts D.C. system and this greatly simplified the conversion of the latter to the higher voltage.

The operation of multiple-unit stock with a series of power units throughout the train made automatic voltage changeover a necessity. The equipment was, however, complex and required a single circuit-breaker for each power unit capable of operating on either voltage. This innovation produced considerable problems, but investigation has shown that one of the principal troubles arose from the constant backfiring by mercury arc rectifiers quite unconnected with the dual voltage system. On the other hand, the erratic performance of the automatic power control equipment, as well as the occasional faulty operation of the circuit-breaker and its "chopping" on the low voltage lines contributed materially to the failures of transformers, motors and auxiliary equipment.

Factors affecting the breakdowns

310. The British Railways' system was in urgent need of modernisation. The Commission's proposals had been announced in their Five Years' Plan, published in January, 1955. The Commission considered it imperative to adhere to that programme although it entailed the electrification of two vital suburban systems and part of a main line, amounting altogether to nearly 700 single-track miles, and the production of over 350 multiple-units and 60 locomotives by the end of 1960—a most formidable programme with new and virtually untried types of electrical equipment.

311. The technical staff of the Commission were limited in number and lacked experience in A.C. traction design and operation. They turned, therefore, to the electric traction industry and invited three firms of great repute to produce efficient equipment, although of different types, in the minimum of time, even though their experience of A.C. traction was also limited. A panel of Consulting Engineers had been appointed to assist the Commission, but they were not called upon to advise on the specifications of the new electrical equipment or to help in their examination and testing.

312. The specifications were widely drawn and it was left to individual firms to develop their own ideas. Their varied approach to this difficult problem can be judged by the variety of solutions offered, both for multiple-units and locomotive equipments, brief particulars of which have been given in Sections IV and V and summarised in Tables 3 to 12.

There was no time to lose in the production of the equipment, but the Contractors accepted the challenge. Late delivery of some early units was a handicap, and it was unfortunate that the equipment was introduced on intensive public services without, as events turned out, sufficient time for proper development and testing.

313. The orders for the electrical equipment for multiple-unit suburban trains were placed at the end of 1956 and for the locomotives early in 1957. Two pilot schemes, namely, the Styal line and the Colchester–Clacton–Walton line, were selected for testing the new electric stock and they were opened for trial running in October, 1958, and February, 1959, respectively. These lines were used for operation

at 25 kV only—the short 6·25 kV section on the Colchester–Clacton line was only used for testing individual units to see that the automatic power control equipment was functioning; it was not used for continuous running. It was not until September, 1959, that the first voltage changeover was available in the Glasgow suburban area and it was not until March, 1960 that a comprehensive dual voltage system was available for trial running; in the Eastern Region practically all of the trial running on the North-East London lines was confined to the 25 kV sections. It seems clear from these facts that the difficulties associated with the dual voltage system were not anticipated and early troubles gave little warning of the breakdowns to come. Attention was confined largely to correcting faults as they arose and efforts were concentrated primarily on getting sufficient units ready for the opening of the public services.

314. Looking back on the events of the past 18 months, I believe that many of the faults experienced in service might have been discovered and put right had more time been allowed for the thorough testing of prototypes before full production began, and had the two pilot schemes been fully equipped and used continuously for testing the dual voltage system with automatic voltage changeover. Such a policy, however, would have entailed the postponement, probably for two years or more, of the electrification of suburban lines badly in need of modernisation, and would have thrown the Five-Year Plan out of gear.

Elimination of faults

315. It is satisfactory to report that, as recorded in earlier sections, all the fundamental faults in the multiple-unit electrical equipment have either been eliminated or modifications are in hand. The transformers, main rectifiers, traction motors and battery chargers are now functioning satisfactorily. The initial difficulties of the automatic power control have been overcome; alterations to the air-blast circuit-breaker are in band and measures have been taken to safeguard the equipment from irregular circuit-breaker operation until its faults are entirely eliminated.

Electrification achievements

316. Up till now attention has been concentrated on the troubles experienced with the new electric traction system and little has been heard of the great measure of success that has been achieved. This has been substantial and striking.

The modified multiple-unit trains of the Glasgow services have established an excellent reputation for punctuality and reliability. They began operating again on 1st October, 1961, and by 31st December they had run for over 1,000,000 unit miles. During these three months the train failure rate from electrical faults averaged one per 70,000 unit miles; all of the faults were of a minor character.

Up to 31st December, 1961, the Glasgow traction motors, which have remained unaltered, had given 8,000,000 motor miles of virtually trouble-free service. The modified Glasgow transformer withstood a test of a severity never previously contemplated and its performance in service has been excellent, though subjected to many short circuits from rectifier backfires. It is of a design similar to that installed in the L.T.S. and Shenfield augmentation stock; these likewise had given trouble-free service for over 13,000,000 unit miles by the end of the year.

The silicon rectifier installed in the 42 units of the Shenfield augmentation stock broke fresh ground in the field of A.C. traction, and it has been an unqualified success. By the end of the year these units had run for 1,500,000 unit miles without a single rectifier failure. This type of rectifier is now to be installed in the North-East London suburban units and in the latest express passenger stock.

On the London Midland Region the A.C. multiple-units are now giving good service and they had run for 1¼ million miles by the end of the year. The A.C. locomotives are doing equally well and they have 1,000,000 miles running to their credit.

Despite the troubles which have received so much adverse publicity, the British Railways' new A.C. multiple-unit fleet operating some of the densest traffic in the world, had run 20,000,000 miles by 31st December, 1961, and this mileage is being increased at a rate of over 1,500,000 unit miles a month.

317. These are achievements of which the Commission and the British electric traction industry may be proud and they demonstrate effectively that the difficulties experienced in the early days of operation have been overcome. I am satisfied that the units now in service will be as reliable, as efficient and as safe as any other A.C. traction units in the world and that the new stock now being developed will give even better service.

Summary

318. In paragraph 305 I posed five questions which I have discussed above. The answers can be summarised as follows:

(i) Having regard to the national interest and mindful of the Commission's intention eventually to extend electrification to many of the main lines, I consider that their decision to adopt the A.C. high voltage system when taken in 1956 was correct.

(ii) (*a*) The cost of providing full 25 kV clearance for the Glasgow and North-East London inner suburban lines would have been prohibitive, hence the adoption of a lower voltage was essential. For the main and outer suburban lines, however, the high voltage system was necessary on economic grounds, thus the dual voltage system was adopted. The operation of multiple-unit stock with motors throughout the train made automatic voltage changeover essential.

(*b*) The failure of equipment unconnected with the dual voltage system was one of the primary causes of breakdown, but the irregular performance of the automatic voltage changeover and the occasional faulty operation of the air-blast circuit-breaker were important contributory factors.

(iii) Had the Commission's and the Contractors' engineers fully appreciated all the serious difficulties that might arise from the introduction of this novel form of electric traction, and had the Commission insisted on longer and more intensive trial running, many troubles might have been avoided, but the additional time needed to ensure reliability before intensive public services were started would seriously have delayed the electrification on suburban lines greatly in need of modernisation, and would have disrupted the Commission's Five-Year Plan.

(iv) All of the fundamental difficulties, including those associated with the dual voltage system, have been overcome; the faults have been eliminated or modifications are in hand.

(v) The multiple-units now in operation are functioning satisfactorily, and by the end of 1961 these trains had run for 20,000,000 miles: they are adding to this impressive score at the rate of over 1,500,000 unit miles a month. These figures demonstrate more effectively than words the great measure of success that has now been achieved.

Overhead clearances

319. Although the problems associated with the dual high voltage system have been solved, automatic voltage changeover still adds to the complexity of the equipment, and it is clearly desirable to reduce to the minimum the areas where such a system must be operated. As I have already explained, this novel feature was introduced so as to ease the clearance problem on those lines where the provision of the full clearance for 25 kV was difficult and costly.

The minimum permissible distance from load gauge to structure for the 25 kV line was 23 in., based on a minimum static electrical clearance of 11 in. and a passing clearance of 8 in. In January, 1960, as a result of a demonstration at Colchester, I suggested to the Commission's engineers that these clearances might be reduced provided adequate tests justified such a course. Since this investigation started the Commission have carried out, at my request, a series of trials to see whether this could be done.

These trials were made under the worst atmospheric conditions in tunnels deliberately filled with smoke and steam, and they have shown that a static clearance of 8 in. and a passing clearance of 6 in. will give an adequate measure of safety for 25 kV lines. The Minister of Transport's Requirements have therefore been revised to permit these reductions at those places where special difficulties arise. As already announced, this modification will enable the London Midland Region's extensive main line electrification between Euston–Crewe–Manchester–Liverpool to be operated throughout at the single voltage of 25 kV. Such a reduction in clearance would not have affected the electrification of the Glasgow and North-East London suburban lines to any appreciable extent, because the available headroom at many of the tunnels and bridges was sufficient only to provide the minimum clearances for 6·25 kV electrification, and costly reconstruction would still have been needed to provide space for 25 kV overhead equipment even with the reduced clearances.

Further developments

320. The British traction engineers—Commission's, Consultants', Contractors'—have built up a wealth of knowledge and experience in the design, construction and operation of multiple-unit electric trains. The achievements recorded in paragrapb 316 by no means cover the whole field of development of A.C. traction in this country. The running of a test train, as described in the Appendix, produced valuable information on the electrical stresses applied to multiple-unit equipment, especially by the operation of the air-blast circuit-breaker, and the important data that has been collected will be of much use to designers in the future.

Seventeen locomotives have now been completed with germanium or silicon semi-conductor rectifiers and rheostatic braking. The rheostatic braking has fulfilled all expectations and the rectifiers bave been trouble-free. A locomotive with transductor control of the low voltage transformer tapping is now completing its works tests. It also includes a silicon main rectifier and a rheostatic brake. The transductor control will give " notchless " control of speed.

Research continues into the production of more advanced types of semi-conductor rectifier; a locomotive with electronic control is in production; devices are being developed to eliminate over-voltages from circuit-breakers when " chopping " on either the 25 kV or the 6·25 kV lines.

Further research is also being undertaken into the design and construction of the overhead equipment with test trains capable of speeds of 100 m.p.h. and fitted with instruments designed to study inter-action between the pantograph and the overhead conductor under all conditions likely to be encountered on British Railways.

Recommendations

321. Simplification of equipment and even greater reliability should be the aim for the future. Special attention should be given to the air-blast circuit-breaker and its components and to the automatic power control equipment. Train unit protection should be reviewed to see whether reliability can be further increased and the number of devices reduced to the essential minimum.

Overhead line protection also requires examination to make sure that it can give rapid back-up protection in the event of the failure of a unit circuit-breaker at particularly vulnerable places, such as 6·25/25 kV voltage changeover neutral sections.

322. Finally, I draw attention to some lack of general co-operation and to some duplication of effort in industrial research which has become apparent to me in the course of my investigation. There are problems still to be solved and new ideas to be developed. Much has been done—more is being done, but further co-operation in research and co-ordination of development are desirable so that the available electric traction resources of this country can be used to the best advantage, not for British Railways solely but in the wider national interest.

A start might be made by establishing more positive arrangements for liaison in research between the British Transport Commission, the Consulting Engineers and the Electric Traction industry, so that there may be fuller exchange of information. Such an arrangement should ensure the maximum use of the lessons of the past, and make available research and development facilities for the benefit of the country as a whole.

British Railways can offer to Industry valuable means of testing prototype rolling stock and equipment. Should future developments warrant such a course, I hope that Industry may acquire in co-operation with the Commission a test track of sufficient length and compound gauge for extensive and high speed trials of new and experimental stock of all gauges for use both at home and abroad. These activities might also be extended to cover diesel and diesel-electric traction.

I am convinced that such co-ordinated effort would stimulate the development of improved forms of railway traction and so ensure the production in this country of the finest railway equipment in the world.

I have the honour to be,

Sir,

Your obedient Servant,

C. A. LANGLEY,

Brigadier.

The Secretary,

Ministry of Transport.

APPENDIX

The G.E.C. Test Train

Introductory

1. At a meeting on 8th January, 1961, with officers of the Commission and the Consulting Engineers, the G.E.C. announced that they would equip a train as a mobile laboratory and provide a team of observers to discover the conditions giving rise to the high transient over-voltages which they believed had damaged the traction motors. At a further meeting two days later the Contractors and representatives of Messrs. Merz and McLennan discussed the equipping of the train and the type of information to be recorded.

2. Unit 408 was selected for the test and the saloon of the motor coach was partly stripped of seats to accommodate the large amount of test equipment. The coach was fitted out at the Contractors' works at Witton, near Birmingham, and on 30th January it was sent to the Eastern Region's electric car shed at Ilford. Some time was needed for checking and calibrating the instruments and in making adjustments so that they would withstand the vibration and movement associated with railway traction. Unit 446 was coupled to the test unit thus making up a 6-car train.

3. The train began operations on 16th February, 1961, on the Liverpool Street–Chingford–Enfield lines, all energised at 6·25 kV.

The test equipment

4. Since the principal object of the service testing was to discover the conditions under which the over-voltages were produced, the measuring equipment had to be capable of recording reliably various phenomena of extremely short duration which might occur at any moment during the course of the tests. Six Cathode Ray Oscillographs (C.R.Os.) were installed; two of these were specially designed for recording very short duration surges and the remainder were standard types adapted for the purpose. All the instruments were arranged so that the electron beam would scan the screen once at high speed and trace out the wave-shape of the transient whenever the applied voltage exceeded a pre-set level. A camera was mounted on the front of each instrument with an open shutter, so as to be ready at all times to record random incidents during the progress of programmed tests.

Capacitor dividers were connected at selected positions in the main power circuit, to feed proportionally scaled-down signal voltages to the instruments. The measuring points covered the pantograph, transformer primary, transformer secondary, transformer tertiary, and the traction motor circuits. In addition, signals proportional to primary current and D.C. motor current were available for measurement. In order to identify the position in sequence of the tap changer, a pulse counter was designed, energised by the notching up of the tap changer. The signals operated a row of lamps in sequence and could also be recorded on a chart.

A 12-channel Ultra-Violet Oscillograph was employed as a continuously running event recorder and twelve of the available quantities were fed to its galvanometers. A chart was thus produced, having a variable rate of feed giving an immediate indication of all variations of the monitored quantities.

5. Meter indication of the primary current, the tertiary current and the train speed was also provided in the test coach. A large number of the tests involved the opening of the air-blast circuit-breaker (A.B.B.) on either of the units forming the test train, and switches were fitted in the test saloon for this purpose, together with lamps showing whether a breaker was closed or open. A further three lamps indicated the tripping of any of the three overload relays on the test unit.

A " point-on-cycle " pulsing device was constructed to enable the opening of the A.B.B. on the test unit to be initiated at any predetermined point on the cycle. This unit could also be arranged to trigger off up to four of the C.R.Os. in synchronism with the opening of the A.B.B.

6. Further hand-operated switches were also fitted for:

(*a*) switching off the excitation of either four or all eight rectifiers;

(*b*) rapid multiple opening and closing of the A.B.B.;

(*c*) synchronising the de-excitation of rectifiers with the tripping of the A.B.B.;

(*d*) short-circuiting certain interlocks in the control circuits.

7. In order to monitor the behaviour of the rectifiers, equipment was installed in the test saloon to register all re-ignition or flash-arcs of each individual cylinder.

8. Equipment was also installed in the guard's van of the test unit which could be connected in circuit experimentally for suppressing surge voltages. This consisted of a variable capacitor and series resistance connected across the transformer secondary and a further capacitor/resistance unit across the tapping choke.

9. Continuous voice inter-communication between test saloon, driving cabs and Unit 446, vital to the success of the testing, was installed. The test apparatus required a 240 volts A.C. supply of up to 3 kW, to be independent of fluctuations in the overhead line supply. To this end, a large 110V battery was used to drive two motor alternator sets which were installed on Unit 446, cables being run up to the test saloon on Unit 408.

10. A G.E.C. team of twelve Engineers was required to carry out the tests, in addition to the railway train and liaison staff. A representative of the Consulting Engineers was also present throughout.

Testing. 16th February to 30th April, 1961

Summary of tests

11. Some 3,000 programmed tests were made and in addition numerous records were taken of random incidents leading to over-voltages. Several hundred static tests were made with the train in a siding, either at Chingford or Wood Street.

12. The programmed tests comprised the opening of the A.B.B. under all the various operating conditions of the train. The variables included:

(*a*) The position of the master controller and of the tap changer in its notching sequence.

(*b*) The position of the train in relation to the feeder point.

(*c*) The train speeds.

(*d*) The primary or line current.

(*e*) The loading on the transformer tertiary winding.

(*f*) The excitation conditions on the rectifiers.

(*g*) The point-on-cycle of the A.B.B. opening.

The majority of the tests were carried out with the minimum service loading on the tertiary winding as it had been found that the coach heating load reduced the level of surges considerably.

13. Testing up to 12th March was carried out with the unit in the " A " modified condition (i.e., mid-point of motors not earthed) with the addition of a protective capacitor unit to prevent premature failure of equipment: this became a major Group " C " Modification (*see* paragraph 226 of the main report). All tests after that date were made with the equipment in the " B " modified condition (i.e., mid-point of motors solidly earthed), some with and others without the protective capacitor.

14. Circuit conditions used for opening the A.B.B. of the test unit included:

(*a*) Master Controller in notch 1 at various speeds.

(*b*) Master Controller in notches 2, 3 and 4 at various speeds.

(*c*) Master Controller in the " off " position, i.e., with the train " coasting ".

(*d*) Tap-changer in course of notching up, or running back to the " off " position.

The conditions were applied with normal rectifier operation and also with the rectifiers operating in a deliberately induced " half-wave " condition.

The latter tests were designed to simulate the conditions following multiple interruption of the current at the pantograph, which, due to certain features of the rectifier excitation, may lead to temporary " half-wave " conditions. A further opening of the A.B.B. can then lead to the generation of severe surges.

15. Tests were also carried out with:

(*e*) A rapid break/make of the A.B.B. with the Controller in position 1. (Rectifiers operating normally.)

This simulated the condition of a single momentary loss of contact between the pantograph and overhead line.

(*f*) A rapid make/break of the A.B.B. with the Controller in the " off " position.

This simulated the closing of the A.B.B. when leaving a neutral section, followed by its immediate tripping due to the operation of the OL3 relay on transformer in-rush current.

(*g*) The A.B.B. of Unit 446 opened under various normal running conditions, to examine its effects upon the test unit.

Some tests were carried out without surge suppression, and others with various degrees of suppression across the transformer secondary winding.

Results

16. An analysis of the test train and laboratory results confirmed that severe over-voltages could be produced by the action of the A.B.B. when running on 6·25 kV with no secondary suppressor fitted to the transformer.

The worst conditions affecting all the transformer windings arose with:

(*a*) The A.B.B. tripping with the rectifiers in the "half-wave" condition. (Up to 7 times the normal peak.)

(*b*) The rapid make/break of the A.B.B. when re-energising after leaving a neutral section. (Up to 6 times the normal peak.)

(*c*) The A.B.B. tripping with the Controller on first notch, and rectifier excitation normal. (Up to 4·5 times the normal peak.)

(*d*) The A.B.B. tripping under normal coasting conditions, e.g., when entering a neutral section with the Controller in the "off" position. (Up to 3·5 times the normal peak.)

With the earth connection at the mid-point of the transformer, condition (*a*) produced over-voltages in the motor circuit of more than 10 kV. When the earth connection was changed to the mid-point of the motor circuit these over-voltages became negligible but voltage surges of over 12 kV to earth were measured on the secondary winding under conditions (*a*) and (*b*) with surges of nearly 2·5 kV in the tertiary winding.

17. The addition of a suppressor on the transformer secondary winding proved effective in limiting the surges to a much lower level. With a 5-microfarads capacitor in series with a 20-ohms resistor across the secondary winding and with the earth at the mid-point of the motor circuit the highest voltages to earth recorded under the worst conditions of (*a*) above were:

26 kV on the primary compared with a normal peak of 8·9 kV.

5·6 kV on the secondary compared with a normal peak of 2·3 kV.

980 volts on the tertiary compared with a normal peak of 380 volts.

It was calculated that the conditions producing these voltages would in turn produce maxima of 5 kV across the D.C. smoothing chokes and 10 kV across the secondary tap changer; it was considered, however, that those voltages would not cause any damage to the equipment.

Various additional means for the suppression of the tertiary voltage to lower values were tried but without success.

18. During the course of the tests with the A.B.B. tripping with the main rectifiers operating on "half-wave", the battery charger unit failed due to voltage breakdown of one of its auxiliary rectifiers. This unit was replaced and test running was resumed, but after only 40 minutes a traction motor failed also, the interpole coils being earthed due to the puncturing of the insulation. The small time interval between the two failures made it almost certain that they were both caused by the same surge. This occurred when the earth connections were still at the mid-point of the transformer and without the addition of a protective capacitor. This failure demonstrated dramatically the effect of over-voltage on the motor circuit as originally planned and confirmed the theoretical conclusions.

Other possible causes of over-voltages

19. A number of other possible causes of over-voltages were examined, with the following results:

(1) The interruption of the current at the pantograph. No direct evidence of serious over-voltages was found, but the position was somewhat confused by the almost simultaneous opening of the A.B.B. Some running was carried out with the A.B.B. prevented from opening under pantograph interruption conditions, but no significant surges were recorded (*see* also paragraph 24).

(2) The interruption of the current by motor contactors. During the many hundreds of operations performed by these contactors, no significant surge voltages were recorded.

(3) Current "chopping" and flash-arcing within the rectifiers. Nothing in the test results indicated this to be a major source of trouble to the motors.

(4) Externally impressed surges from the overhead line supply. No cases of this were revealed. The supply voltage was subject to some fluctuation, and considerable distortion of its wave-form due to the action of other trains was observed, but there were no violent disturbances.

Behaviour of rectifiers

20. Whilst a considerable number of flash-arcs occurred at night when the train was left with its pantograph up, very few occurred whilst testing was in progress. Of the latter group none gave rise

to surge voltages or tripping of the overload relay. Some flash-arcs were deliberately induced by mechanical impact by allowing abnormally high coolant temperature, and by fitting suspect rectifiers, but no significant surges were recorded.

Random incidents producing over-voltages

21. A number of incidents leading to substantial over-voltages were recorded. The maxima were:

Primary circuit	..	47 kV.
Secondary circuit	..	8·4 kV.
Tertiary circuit	..	1·12 kV.

This is an important aspect of the testing, since it reflects the operation of the equipment in normal running. There were, however, no cases of random incidents producing over-voltages greater in value than those observed during the programmed tests.

Testing. 1st May to 31st July, 1961

Preliminary remarks

22. After 30th April, 1961, only a limited amount of voltage surge testing was undertaken and attention was concentrated primarily on examining the ability of the Com-Pak rectifier to fulfil the duty imposed on it when working on an intensified suburban service.

Voltage surges

23. The object of the further voltage surge tests was to ascertain the peak voltage likely to be imposed on the tertiary circuit after the " C " and other modifications had been carried out (*see* paragraphs 226 to 230 of the main report). The following results were recorded:

(*a*) *Excitation silicon diodes for the main rectifier.* The normal peak voltage recorded was in the order of 200 volts with an exceptional peak of 500 volts. To cope with this, a small surge absorber was inserted in the silicon diode circuit.

(*b*) *Auxiliary fan motor capacitor.* Tests were made to ascertain a maximum voltage which could be imposed on these capacitors so as to assist design requirements for similar machines to be used in multiple-unit express stock. A peak of 1,120 volts was recorded.

(*c*) *Tertiary circuit.* Even with the full suppression fitted, a peak of 980 volts in the tertiary circuit was recorded, but this only occurred during " half-wave " rectification (*see* paragraph 214 of the main report). The chance of further trouble from this source has been greatly reduced by improvements in the overhead equipment and by the slowing down of the A.B.B. opening under normal power interruption (*see* paragraph 232). It will be eliminated entirely when silicon semi-conductors replace the Com-Pak rectifiers (*see* paragraph 236).

Interruption of the current at the pantograph

24. A further series of tests was made to establish whether current " chopping " from pantograph " bounce " could produce any surges of consequence in the train equipment. For this purpose high-speed runs were made with the A.B.B. no-voltage relays rendered inoperative. On one trip 11 pantograph " bounces " were recorded but none of them caused any over-voltages.

Rectifier tests

25. The purpose of these tests was to examine in great detail the working parameters of the rectifier to determine whether any combination of conditions existed which would assist in finding solutions of the troubles that had been experienced. The test train was run for some 2,000 miles and a summary of the results is given in paragraphs 26–29.

Vacuum condition

26. All the eight rectifiers were deliberately allowed to overheat. Two backfired and one cylinder had a reduced vacuum, but it was still in a workable condition.

Current surges during backfire

27. The current surges through the primary circuit were measured during backfire from which current through the transformer secondary winding was calculated. The worst conditions arose when the motors were running at half power (tap changer in notch 10) when a primary peak of 1,500 amps was recorded; this was equivalent to a peak of about 10,300 amps through the secondary winding. On the other hand with power full on (tap changer in notch 19) the primary peak was 2,300 amps which produced a peak of about 7,700 amps in the secondary winding.

Rectifier cooling circuit

28. In the course of the tests during the summer a blanket of hot air produced by various mechanical and electrical losses travelled along with the train on calm days producing a local temperature around the cooling fan inlet several degrees higher than the atmospheric shade temperature. Modifications were made in the cooling arrangements which enabled the effect of the temperature of the static area to be reduced by some 10° C.

Excitation equipment

29. Arc extinction and re-ignition from pantograph " bounce " were induced during the early tests but with the improvements of the overhead equipment and the slowing down of the A.B.B. opening, as already mentioned, this source of trouble has been virtually eliminated. Silicon diodes were substituted for the original selenium auxiliary rectifiers which had failed to withstand the high voltage surges. The first of the new diodes also failed but the addition of silicon carbide diverters gave the requisite protection and these diodes are now operating perfectly.

Transformer in-rush currents

30. Initial in-rush currents up to 1,000 amps were recorded, though the majority were usually less than 500 amps.

Line voltages

31. A careful observance of the line voltage was made throughout the test period and it was found that during periods of light loading on the Liverpool Street–Southend (Victoria) line, the line voltage on the 6·25 kV system could rise to 7·2 kV for considerable periods, compared with the specified maximum of 6·9 kV. The higher voltage gave a corresponding tertiary voltage of 320 volts compared with the normal voltage of 270 volts when operating at standard voltage on the 25 kV line.

Conclusions

32. All these tests have been carried out on the 6·25 kV lines of the Eastern Region. The earlier ones were on the North-East London Suburban lines and the later tests were on the Liverpool Street–Southend (Victoria) line. They have produced valuable information on the operation of multiple-unit equipment under the most arduous conditions of service. They have demonstrated the effect of current " chopping " and pantograph " bounce " and have shown that very high surges could be impressed on both the secondary and tertiary circuits. They have confirmed the efficiency of the various remedial measures that have been taken to cope with these surges. A vast quantity of valuable and important data has been collected and it will be of great use in the future to British designers of A.C. electric traction equipment.

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MINISTRY OF TRANSPORT

RAILWAY ACCIDENTS

Final Report on the Accidents and Failures that occurred in Multiple-unit Electric Trains in the Scottish Region and Eastern Region British Railways

LONDON: HER MAJESTY'S STATIONERY OFFICE
1962

CONTENTS

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